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(54) Title: HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM EMPLOYING MULTI-CARRIER MODULATION

(57) Abstract: Transmitter and receiver units for use in a communications system and configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals. The transmitter unit includes a system data processor, one or more modulators, and one or more antennas. The system data processor receives and partitions an input data stream into a number of channel data streams and further processes the channel data streams to generate one or more modulation symbol vector streams. Each modulation symbol vector stream includes a sequence of modulation symbol vectors representative of data in one or more channel data streams. Each modulator receives and modulates a respective modulation symbol vector stream to provide an RF modulated signal, and each antenna receives and transmits a respective RF modulated signal. Each modulator may include an inverse (fast) Fourier transform (IFFT) and a cyclic prefix generator. The IFFT generates time-domain representations of the modulation symbol vectors, and the cyclic prefix generator repeats a portion of the time-domain representation of each modulation symbol vector. The channel data streams are modulated using multi-carrier modulation, e.g., OFDM modulation. Time division multiplexing (TDM) may also be used to increase flexibility.

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HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM EMPLOYING MULTI-CARRIER MODULATION

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to data communication. More particularly, the present invention relates to a novel and improved communications system employing multi-carrier modulation and having high efficiency, improved performance, and enhanced flexibility.

II. Description of the Related Art

A modern day communications system is required to support a variety of applications. One such communications system is a code division multiple access (CDMA) system that conforms to the "TIA/EIA/IS-95 Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," hereinafter referred to as the IS-95 standard. The CDMA system supports voice and data communication between users over a terrestrial link. The use of CDMA techniques in a multiple access communication system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM," both assigned to the assignee of the present invention and incorporated herein by reference.

An IS-95 compliant CDMA system is capable of supporting voice and data services over the forward and reverse communications links. Typically, each voice call or each traffic data transmission is assigned a dedicated channel having a variable but limited data rate. In accordance with the IS-95 standard, the traffic or voice data is partitioned into code channel frames that are 20 msec in duration with data rates as high as 14.4 Kbps. The frames are then transmitted over the assigned channel. A method for transmitting traffic data in code channel frames of fixed size is described in U.S. Patent No. 5,504,773, entitled "METHOD AND APPARATUS FOR THE FORMATTING OF DATA FOR TRANSMISSION,"

assigned to the assignee of the present invention and incorporated herein by reference.

A number of significant differences exist between the characteristics and requirements of voice and data services. One such difference is the fact that voice services impose stringent and fixed delay requirements whereas data services can usually tolerate variable amounts of delay. The overall one-way delay of speech frames is typically required to be less than 100 msec. In contrast, the delay for data frames is typically a variable parameter that can be advantageously used to optimize the overall efficiency of the data communications system.

The higher tolerance to delay allows traffic data to be aggregated and transmitted in bursts, which can provide a higher level of efficiency and performance. For example, data frames may employ more efficient error correcting coding techniques requiring longer delays that cannot be tolerated by voice frames. In contrast, voice frames may be limited to the use of less efficient coding techniques having shorter delays.

Another significant difference between voice and data services is that the former typically requires a fixed and common grade of service (GOS) for all users, which is usually not required or implemented for the latter. For digital communications systems providing voice services, this typically translates into a fixed and equal transmission rate for all users and a maximum tolerable value for the error rate of speech frames. In contrast, for data services, the GOS may be different from user to user and is also typically a parameter that can be advantageously optimized to increase the overall efficiency of the system. The GOS of a data communications system is typically defined as the total delay incurred in the transfer of a particular amount of data.

Yet another significant difference between voice and data services is that the former require a reliable communications link that, in a CDMA system, is provided by soft handoff. Soft handoff results in redundant transmissions from two or more base stations to improve reliability. However, this additional reliability may not be required for data transmission because data frames received in error may be retransmitted. For data services, the transmit power needed to support soft handoff may be more efficiently used for transmitting additional data.

Because of the significant differences noted above, it is a challenge to design a communications system capable of efficiently supporting both voice and data services. The IS-95 CDMA system is designed to efficiently

transmit voice data, and is also capable of transmitting traffic data. The design of the channel structure and the data frame format pursuant to IS-95 have been optimized for voice data. A communications system based on IS-95 that is enhanced for data services is disclosed in U.S. Patent Application Serial No. 08/963,386, entitled "METHOD AND APPARATUS FOR HIGH RATE PACKET DATA TRANSMISSION," filed November 3, 1997, assigned to the assignee of the present invention and incorporated herein by reference.

Given the ever-growing demand for wireless voice and data communication, however a higher efficiency, higher performance wireless communications system capable of supporting voice and data services is desirable.

SUMMARY OF THE INVENTION

The present invention is directed to a novel and improved communications system capable of providing increased spectral efficiency, improved performance, and enhanced flexibility by employing a combination of antenna, frequency, and temporal diversity. The communications system can be operative to concurrently support a number of transmissions of various types (e.g., control, broadcast, voice, traffic data, and so on) that may have disparate requirements. Various aspects, features, and embodiments of the communications system are described below.

An embodiment of the invention provides a transmitter unit for use in a communications system and configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals. The transmitter unit includes a system data processor, one or more modulators, and one or more antennas. The system data processor receives and partitions an input data stream into a number of (K) channel data streams and further processes the channel data streams to generate one or more (N_T) modulation symbol vector streams. Each modulation symbol vector stream includes a sequence of modulation symbol vectors representative of data in one or more channel data streams.

Each modulator modulates a respective modulation symbol vector stream to provide a modulated signal, and each antenna receives and transmits a respective modulated signal. Each modulator typically includes an inverse (fast) Fourier transform (IFFT) and a cyclic prefix generator. The IFFT generates time-domain representations of the modulation symbol

vectors, and the cyclic prefix generator repeats a portion of the time-domain representation of each modulation symbol vector.

The system data processor may include one or more channel data processors, encoders, demultiplexers, and combiners. In a specific implementation, each encoder encodes a respective channel data stream to generate an encoded data stream, each channel data processor processes a respective encoded data stream to generate a stream of modulation symbols, each demultiplexer demultiplexes the stream of modulation symbols into one or more symbol sub-streams, and each combiner selectively combines the symbol sub-streams to generate a modulation symbol vector stream for an associated antenna.

In accordance with an aspect of the invention, the channel data streams are modulated using multi-carrier modulation (e.g., orthogonal frequency division multiplexing (OFDM) modulation). The multi-carrier modulation partitions the system operating bandwidth, W, into a number of (L) sub-bands. Each sub-band is associated with a different center frequency and corresponds to one sub-channel.

The modulation symbol vectors are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof. For example, the data for a particular channel data stream may be transmitted from one or more antennas, on one or more sub-bands of the system operating bandwidth, and at one or more time periods to respectively provide antenna, frequency, and temporal diversity. Various communications modes (e.g., diversity and MIMO) may be supported and are described in greater detail below.

Each channel data stream, each sub-channel, each antenna, or some other unit of transmission can be modulated with a particular modulation scheme selected from a set that includes, for example, M-PSK and M-QAM. The encoding can be achieved on each channel data stream, each sub-channel, and so on. Pre-conditioning of the data may also be performed at the transmitter unit using channel state information (CSI) descriptive of the characteristics of the communications links. Such CSI may include, for example, the eigenmodes corresponding to, or the C/I values for, the communications links, which are described below.

Time division multiplexing (TDM) may also be used to increase flexibility, especially for traffic data transmission. The channel data streams may thus be transmitted in time slots, with each time slot having a duration that is related to, for example, the length of a modulation symbol. A voice

call may be assigned a portion of the available system resources (e.g., a particular sub-channel) to minimize processing delay. Traffic data for a particular transmission may be aggregated and transmitted in one or more time slots for improved efficiency. Pilot and other types of data may also be multiplexed and transmitted on selected time slots.

Another embodiment of the invention provides a receiver unit that includes, for example, at least one antenna, at least one front end processor, at least one (fast) Fourier transform (FFT), a processor, at least one demodulator, and at least one decoder. Each antenna receives one or more modulated signals and provides the received signal to a respective front end processor that processes the signal to generate samples. Each FFT converts the samples from a respective front end processor into transformed representations. The transformed representations from the at least one FFT processor are then processed by the processor into one or more symbol streams, with each symbol stream corresponding to a particular transmission (e.g., control, broadcast, voice, or traffic data) being processed.

Each demodulator demodulates a respective symbol stream to generate demodulated data, and each decoder decodes respective demodulated data to generate decoded data. The modulated signals are generated and transmitted and/or received in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof, as described below.

Yet another embodiment of the invention provides a method for generating and transmitting one or more modulated signals. In accordance with the method, an input data stream is received and partitioned into a number of channel data streams. The channel data streams are then encoded with one or more encoding schemes and modulated with one or more modulation schemes to generate modulation symbols. Symbols corresponding to the sub-channels of each antenna are then combined into modulation symbol vectors, which are then provided as a modulation symbol vector stream. Again, the modulation symbol vectors are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when

taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1 is a diagram of a multiple-input multiple-output (MIMO) communications system;

FIG. 2 is a diagram that graphically illustrates a specific example of a transmission from a transmit antenna at a transmitter unit;

FIG. 3 is a block diagram of an embodiment of a data processor and a modulator of the communications system shown in FIG. 1;

FIGS. 4A and 4B are block diagrams of two embodiments of a channel data processor that can be used for processing one channel data steam such as control, broadcast, voice, or traffic data;

FIGS. 5A through 5C are block diagrams of an embodiment of the processing units that can be used to generate the transmit signal shown in FIG. 2;

FIG. 6 is a block diagram of an embodiment of a receiver unit, having multiple receive antennas, which can be used to receive one or more channel data streams; and

FIG. 7 shows plots that illustrate the spectral efficiency achievable with some of the operating modes of a communications system in accordance with one embodiment.

DETAILED DESCRIPTION OF THE SPECIFIC EMBODIMENTS

FIG. 1 is a diagram of a multiple-input multiple-output (MIMO) communications system 100 capable of implementing some embodiments of the invention. Communications system 100 can be operative to provide a combination of antenna, frequency, and temporal diversity to increase spectral efficiency, improve performance, and enhance flexibility. Increased spectral efficiency is characterized by the ability to transmit more bits per second per Hertz (bps/Hz) when and where possible to better utilize the available system bandwidth. Techniques to obtain higher spectral efficiency are described in further detail below. Improved performance may be quantified, for example, by a lower bit-error-rate (BER) or frame-error-rate (FER) for a given link carrier-to-noise-plus-interference ratio (C/I). And enhanced flexibility is characterized by the ability to accommodate multiple users having different and typically disparate requirements. These goals may be achieved, in part, by employing multi-carrier modulation, time division multiplexing (TDM), multiple transmit and/or receive antennas,

and other techniques. The features, aspects, and advantages of the invention are described in further detail below.

As shown in FIG. 1, communications system 100 includes a first system 110 in communication with a second system 120. System 110 includes a (transmit) data processor 112 that (1) receives or generates data, (2) processes the data to provide antenna, frequency, or temporal diversity, or a combination thereof, and (3) provides processed modulation symbols to a number of modulators (MOD) 114a through 114t. Each modulator 114 further processes the modulation symbols and generates an RF modulated signal suitable for transmission. The RF modulated signals from modulators 114a through 114t are then transmitted from respective antennas 116a through 116t over communications links 118 to system 120.

In the embodiment shown in FIG. 1, system 120 includes a number of receive antennas 122a through 122r that receive the transmitted signals and provide the received signals to respective demodulators (DEMOD) 124a through 124r. As shown in FIG. 1, each receive antenna 122 may receive signals from one or more transmit antennas 116 depending on a number of factors such as, for example, the operating mode used at system 110, the directivity of the transmit and receive antennas, the characteristics of the communications links, and others. Each demodulator 124 demodulates the respective received signal using a demodulation scheme that is complementary to the modulation scheme used at the transmitter. The demodulated symbols from demodulators 124a through 124r are then provided to a (receive) data processor 126 that further processes the symbols to provide the output data. The data processing at the transmitter and receiver units is described in further detail below.

FIG. 1 shows only the forward link transmission from system 110 to system 120. This configuration may be used for data broadcast and other one-way data transmission applications. In a bi-directional communications system, a reverse link from system 120 to system 110 is also provided, although not shown in FIG. 1 for simplicity. For the bi-directional communications system, each of systems 110 and 120 may operate as a transmitter unit or a receiver unit, or both concurrently, depending on whether data is being transmitted from, or received at, the unit.

For simplicity, communications system 100 is shown to include one transmitter unit (i.e., system 110) and one receiver unit (i.e., system 120). However, other variations and configurations of the communications system are possible. For example, in a multi-user, multiple access

communications system, a single transmitter unit may be used to concurrently transmit data to a number of receiver units. Also, in a manner similar to soft-handoff in an IS-95 CDMA system, a receiver unit may concurrently receive transmissions from a number of transmitter units. The communications system of the invention may include any number of transmitter and receiver units.

Each transmitter unit may include a single transmit antenna or a number of transmit antennas, such as that shown in FIG. 1. Similarly, each receiver unit may include a single receive antenna or a number of receive antennas, again such as that shown in FIG. 1. For example, the communications system may include a central system (i.e., similar to a base station in the IS-95 CDMA system) having a number of antennas that transmit data to, and receive data from, a number of remote systems (i.e., subscriber units, similar to remote stations in the CDMA system), some of which may include one antenna and others of which may include multiple antennas. Generally, as the number of transmit and receive antennas increases, antenna diversity increases and performance improves, as described below.

As used herein, an antenna refers to a collection of one or more antenna elements that are distributed in space. The antenna elements may be physically located at a single site or distributed over multiple sites. Antenna elements physically co-located at a single site may be operated as an antenna array (e.g., such as for a CDMA base station). An antenna network consists of a collection of antenna arrays or elements that are physically separated (e.g., several CDMA base stations). An antenna array or an antenna network may be designed with the ability to form beams and to transmit multiple beams from the antenna array or network. For example, a CDMA base station may be designed with the capability to transmit up to three beams to three different sections of a coverage area (or sectors) from the same antenna array. Thus, the three beams may be viewed as three transmissions from three antennas.

The communications system of the invention can be designed to provide a multi-user, multiple access communications scheme capable of supporting subscriber units having different requirements as well as capabilities. The scheme allows the system's total operating bandwidth, W, (e.g., 1.2288 MHz) to be efficiently shared among different types of services that may have highly disparate data rate, delay, and quality of service (QOS) requirements.

Examples of such disparate types of services include voice services and data services. Voice services are typically characterized by a low data rate (e.g., 8 kbps to 32 kbps), short processing delay (e.g., 3 msec to 100 msec overall one-way delay), and sustained use of a communications channel for an extended period of time. The short delay requirements imposed by voice services typically require a small fraction of the system resources to be dedicated to each voice call for the duration of the call. In contrast, data services are characterized by "bursty" traffics in which variable amounts of data are sent at sporadic times. The amount of data can vary significantly from burst-to-burst and from user-to-user. For high efficiency, the communications system of the invention can be designed with the capability to allocate a portion of the available resources to voice services as required and the remaining resources to data services. In some embodiments of the invention, a fraction of the available system resources may also be dedicated for certain data services or certain types of data services.

The distribution of data rates achievable by each subscriber unit can vary widely between some minimum and maximum instantaneous values (e.g., from 200 kbps to over 20 Mbps). The achievable data rate for a particular subscriber unit at any given moment may be influenced by a number of factors such as the amount of available transmit power, the quality of the communications link (i.e., the C/I), the coding scheme, and others. The data rate requirement of each subscriber unit may also vary widely between a minimum value (e.g., 8 kbps, for a voice call) all the way up to the maximum supported instantaneous peak rate (e.g., 20 Mbps for bursty data services).

The percentage of voice and data traffic is typically a random variable that changes over time. In accordance with certain aspects of the invention, to efficiently support both types of services concurrently, the communications system of the invention is designed with the capability to dynamic allocate the available resources based on the amount of voice and data traffic. A scheme to dynamically allocate resources is described below. Another scheme to allocate resources is described in the aforementioned U.S. Patent Application Serial No. 08/963,386.

The communications system of the invention provides the above-described features and advantages, and is capable of supporting different types of services having disparate requirements. The features are achieved by employing antenna, frequency, or temporal diversity, or a combination

thereof. In some embodiments of the invention, antenna, frequency, or temporal diversity can be independently achieved and dynamically selected.

As used herein, antenna diversity refers to the transmission and/or reception of data over more than one antenna, frequency diversity refers to the transmission of data over more than one sub-band, and temporal diversity refers to the transmission of data over more than one time period. Antenna, frequency, and temporal diversity may include subcategories. For example, transmit diversity refers to the use of more than one transmit antenna in a manner to improve the reliability of the communications link, receive diversity refers to the use of more than one receive antenna in a manner to improve the reliability of the communications link, and spatial diversity refers to the use of multiple transmit and receive antennas to improve the reliability and/or increase the capacity of the communications link. Transmit and receive diversity can also be used in combination to improve the reliability of the communications link without increasing the link capacity. Various combinations of antenna, frequency, and temporal diversity can thus be achieved and are within the scope of the present invention.

Frequency diversity can be provided by use of a multi-carrier modulation scheme such as orthogonal frequency division multiplexing (OFDM), which allows for transmission of data over various sub-bands of the operating bandwidth. Temporal diversity is achieved by transmitting the data over different times, which can be more easily accomplished with the use of time-division multiplexing (TDM). These various aspects of the communications system of the invention are described in further detail below.

In accordance with an aspect of the invention, antenna diversity is achieved by employing a number of (N_T) transmit antennas at the transmitter unit or a number of (N_R) receive antennas at the receiver unit, or multiple antennas at both the transmitter and receiver units. In a terrestrial communications system (e.g., a cellular system, a broadcast system, an MMDS system, and others), an RF modulated signal from a transmitter unit may reach the receiver unit via a number of transmission paths. The characteristics of the transmission paths typically vary over time based on a number of factors. If more than one transmit or receive antenna is used, and if the transmission paths between the transmit and receive antennas are independent (i.e., uncorrelated), which is generally true to at least an extent, then the likelihood of correctly receiving the transmitted

signal increases as the number of antennas increases. Generally, as the number of transmit and receive antennas increases, diversity increases and performance improves.

In some embodiments of the invention, antenna diversity is dynamically provided based on the characteristics of the communications link to provide the required performance. For example, higher degree of antenna diversity can be provided for some types of communication (e.g., signaling), for some types of services (e.g., voice), for some communications link characteristics (e.g., low C/I), or for some other conditions or considerations.

As used herein, antenna diversity includes transmit diversity and receive diversity. For transmit diversity, data is transmitted over multiple transmit antennas. Typically, additional processing is performed on the data transmitted from the transmit antennas to achieved the desired diversity. For example, the data transmitted from different transmit antennas may be delayed or reordered in time, or coded and interleaved across the available transmit antennas. Also, frequency and temporal diversity may be used in conjunction with the different transmit antennas. For receive diversity, modulated signals are received on multiple receive antennas, and diversity is achieved by simply receiving the signals via different transmission paths.

In accordance with another aspect of the invention, frequency diversity can be achieved by employing a multi-carrier modulation scheme. One such scheme that has numerous advantages is OFDM. With OFDM modulation, the overall transmission channel is essentially divided into a number of (L) parallel sub-channels that are used to transmit the same or different data. The overall transmission channel occupies the total operating bandwidth of W, and each of the sub-channels occupies a sub-band having a bandwidth of W/L and centered at a different center frequency. Each sub-channel has a bandwidth that is a portion of the total operating bandwidth. Each of the sub-channels may also be considered an independent data transmission channel that may be associated with a particular (and possibly unique) processing, coding, and modulation scheme, as described below.

The data may be partitioned and transmitted over any defined set of two or more sub-bands to provide frequency diversity. For example, the transmission to a particular subscriber unit may occur over sub-channel 1 at time slot 1, sub-channel 5 at time slot 2, sub-channel 2 at time slot 3, and so on. As another example, data for a particular subscriber unit may be

transmitted over sub-channels 1 and 2 at time slot 1 (e.g., with the same data being transmitted on both sub-channels), sub-channels 4 and 6 at time slot 2, only sub-channel 2 at time slot 3, and so on. Transmission of data over different sub-channels over time can improve the performance of a communications system experiencing frequency selective fading and channel distortion. Other benefits of OFDM modulation are described below.

In accordance with yet another aspect of the invention, temporal diversity is achieved by transmitting data at different times, which can be more easily accomplished using time division multiplexing (TDM). For data services (and possibly for voice services), data transmission occurs over time slots that may be selected to provide immunity to time dependent degradation in the communications link. Temporal diversity may also be achieved through the use of interleaving.

For example, the transmission to a particular subscriber unit may occur over time slots 1 through x, or on a subset of the possible time slots from 1 through x (e.g., time slots 1, 5, 8, and so on). The amount of data transmitted at each time slot may be variable or fixed. Transmission over multiple time slots improves the likelihood of correct data reception due to, for example, impulse noise and interference.

The combination of antenna, frequency, and temporal diversity allows the communications system of the invention to provide robust performance. Antenna, frequency, and/or temporal diversity improves the likelihood of correct reception of at least some of the transmitted data, which may then be used (e.g., through decoding) to correct for some errors that may have occurred in the other transmissions. The combination of antenna, frequency, and temporal diversity also allows the communications system to concurrently accommodate different types of services having disparate data rate, processing delay, and quality of service requirements.

The communications system of the invention can be designed and operated in a number of different communications modes, with each communications mode employing antenna, frequency, or temporal diversity, or a combination thereof. The communications modes include, for example, a diversity communications mode and a MIMO communications mode. Various combinations of the diversity and MIMO communications modes can also be supported by the communications system. Also, other communications modes can be implemented and are within the scope of the present invention.

The diversity communications mode employs transmit and/or receive diversity, frequency, or temporal diversity, or a combination thereof, and is generally used to improve the reliability of the communications link. In one implementation of the diversity communications mode, the transmitter unit selects a modulation and coding scheme (i.e., configuration) from a finite set of possible configurations, which are known to the receiver units. For example, each overhead and common channel may be associated with a particular configuration that is known to all receiver units. When using the diversity communications mode for a specific user (e.g., for a voice call or a data transmission), the mode and/or configuration may be known a priori (e.g., from a previous set up) or negotiated (e.g., via a common channel) by the receiver unit.

In the diversity communications mode, data is transmitted on one or more sub-channels, from one or more antennas, and at one or more time periods. The allocated sub-channels may be associated with the same antenna, or may be sub-channels associated with different antennas. In a common application of the diversity communications mode, which is also referred to as a "pure" diversity communications mode, data is transmitted from all available transmit antennas to the destination receiver unit. The pure diversity communications mode can be used in instances where the data rate requirements are low or when the C/I is low, or when both are true.

The MIMO communications mode employs antenna diversity at both ends of the communication link and is generally used to improve both the reliability and increase the capacity of the communications link. The MIMO communications mode may further employ frequency and/or temporal diversity in combination with the antenna diversity. The MIMO communications mode, which may also be referred to herein as the spatial communications mode, employs one or more processing modes to be described below.

The diversity communications mode generally has lower spectral efficiency than the MIMO communications mode, especially at high C/I levels. However, at low to moderate C/I values, the diversity communications mode achieves comparable efficiency and can be simpler to implement. In general, the use of the MIMO communications mode provides greater spectral efficiency when used, particularly at moderate to high C/I values. The MIMO communications mode may thus be advantageously used when the data rate requirements are moderate to high.

The communications system can be designed to concurrently support both diversity and MIMO communications modes. The communications modes can be applied in various manners and, for increased flexibility, may be applied independently on a sub-channel basis. The MIMO communications mode is typically applied to specific users. However, each communications mode may be applied on each sub-channel independently, across a subset of sub-channels, across all sub-channels, or on some other basis. For example, the use of the MIMO communications mode may be applied to a specific user (e.g., a data user) and, concurrently, the use of the diversity communications mode may be applied to another specific user (e.g., a voice user) on a different sub-channel. The diversity communications mode may also be applied, for example, on sub-channels experiencing higher path loss.

The communications system of the invention can also be designed to support a number of processing modes. When the transmitter unit is provided with information indicative of the conditions (i.e., the "state") of the communications links, additional processing can be performed at the transmitter unit to further improve performance and increase efficiency. Full channel state information (CSI) or partial CSI may be available to the transmitter unit. Full CSI includes sufficient characterization of the propagation path (i.e., amplitude and phase) between all pairs of transmit and receive antennas for each sub-band. Full CSI also includes the C/I per sub-band. The full CSI may be embodied in a set of matrices of complex gain values that are descriptive of the conditions of the transmission paths from the transmit antennas to the receive antennas, as described below. Partial CSI may include, for example, the C/I of the sub-band . With full CSI or partial CSI, the transmitter unit pre-conditions the data prior to transmission to receiver unit.

In a specific implementation of the full-CSI processing mode, the transmitter unit preconditions the signals presented to the transmit antennas in a way that is unique to a specific receiver unit (e.g., the pre-conditioning is performed for each sub-band assigned to that receiver unit). As long as the channel does not change appreciably from the time it is measured by the receiver unit and subsequently sent back to the transmitter and used to precondition the transmission, the intended receiver unit can demodulate the transmission. In this implementation, a full-CSI based MIMO communication can only be demodulated by the receiver unit associated with the CSI used to precondition the transmitted signals.

In a specific implementation of the partial-CSI or no-CSI processing modes, the transmitter unit employs a common modulation and coding scheme (e.g., on each data channel transmission), which then can be (in theory) demodulated by all receiver units. In an implementation of the partial-CSI processing mode, a single receiver unit can specify it's C/I, and the modulation employed on all antennas can be selected accordingly (e.g., for reliable transmission) for that receiver unit. Other receiver units can attempt to demodulate the transmission and, if they have adequate C/I, may be able to successfully recover the transmission. A common (e.g., broadcast) channel can use a no-CSI processing mode to reach all users.

The full-CSI processing is briefly described below. When the CSI is available at the transmitter unit, a simple approach is to decompose the multi-input multi-output channel into a set of independent channels. Given the channel transfer function at the transmitters, the left eigenvectors may be used to transmit different data streams. The modulation alphabet used with each eigenvector is determined by the available C/I of that mode, given by the eigenvalues. If **H** is the N_R x N_T matrix that gives the channel response for the N_T transmitter antenna elements and N_R receiver antenna elements at a specific time, and $\underline{\mathbf{x}}$ is the N_T-vector of inputs to the channel, then the received signal can be expressed as:

$$\underline{\mathbf{y}} = \mathbf{H}\underline{\mathbf{x}} + \underline{\mathbf{n}} ,$$

where $\underline{\mathbf{n}}$ is an N_R-vector representing noise plus interference. The eigenvector decomposition of the Hermitian matrix formed by the product of the channel matrix with its conjugate-transpose can be expressed as:

$$\mathbf{H}^*\mathbf{H} = E\ddot{\mathbf{E}}E^* ,$$

where the symbol * denotes conjugate-transpose, E is the eigenvector matrix, and $\ddot{\mathbf{E}}$ is a diagonal matrix of eigenvalues, both of dimension N_TxN_T.The transmitter converts a set of N_T modulation symbols $\underline{\mathbf{b}}$ using the eigenvector matrix E. The transmitted modulation symbols from the N_T transmit antennas can thus be expressed as:

$$\underline{\mathbf{x}} = E\underline{\mathbf{b}} .$$

For all antennas, the pre-conditioning can thus be achieved by a matrix multiply operation expressed as:

$$\begin{bmatrix} x_1 \\ x_2 \\ \mathrm{M} \\ x_{N_T} \end{bmatrix} = \begin{bmatrix} e_{11}, & e_{12}, & e_{1N_T} \\ e_{21}, & e_{22}, & e_{2N_T} \\ & & \\ e_{N_T1}, & e_{N_T1}, & e_{N_TN_T} \end{bmatrix} \bullet \begin{bmatrix} b_1 \\ b_2 \\ \mathrm{M} \\ b_{N_T} \end{bmatrix} \qquad \text{Eq (1)}$$

where b_1, b_2, ... and b_{NT} are respectively the modulation symbols for a particular sub-channel at transmit antennas 1, 2, ... N_T, where each modulation symbol can be generated using, for example, M-PSK, M-QAM, and so on, as described below;

E = is the eigenvector matrix related to the transmission loss from transmit antennas to the receive antennas; and

x_1, x_2, ... x_{NT} are the pre-conditioned modulation symbols, which can be expressed as:

$$x_1 = b_1 \bullet e_{11} + b_2 \bullet e_{12} + \ \ldots \ + b_{N_T} \bullet e_{1N_T} \ ,$$

$$x_2 = b_1 \bullet e_{21} + b_2 \bullet e_{22} + \ \ldots \ + b_{N_T} \bullet e_{2N_T} \ , \text{and}$$

$$x_{N_T} = b_1 \bullet e_{N_T1} + b_2 \bullet e_{N_T2} + \ \ldots \ + b_{N_T} \bullet e_{N_TN_T} \ .$$

Since H*H is Hermitian, the eigenvector matrix is unitary. Thus, if the elements of $\underline{\mathbf{b}}$ have equal power, the elements of $\underline{\mathbf{x}}$ also have equal power. The received signal may then be expressed as:

$$\underline{\mathbf{y}} = \mathbf{HE}\underline{\mathbf{b}} + \underline{\mathbf{n}} \ .$$

The receiver performs a channel-matched-filter operation, followed by multiplication by the right eigenvectors. The result of the channel-matched-filter operation is the vector $\underline{\mathbf{z}}$, which can be expressed as:

$$\underline{\mathbf{z}} = E^*\mathbf{H}^*\mathbf{H}E\underline{\mathbf{b}} + E^*\mathbf{H}^*\underline{\mathbf{n}} = \ddot{\mathbf{E}}\underline{\mathbf{b}} + \underline{\hat{\mathbf{n}}} \ , \qquad \text{Eq.(2)}$$

where the new noise term has covariance that can be expressed as:

$$E(\underline{\hat{n}\hat{n}^*}) = E(E^*\mathbf{H}^*\underline{\mathbf{nn}^*}\mathbf{H}E) = E^*\mathbf{H}^*\mathbf{H}E = \Lambda \ ,$$

i.e., the noise components are independent with variance given by the eigenvalues. The C/I of the i-th component of $\underline{\mathbf{z}}$ is λ_i, the i-th diagonal element of $\ddot{\mathbf{E}}$.

The transmitter unit can thus select a modulation alphabet (i.e., signal constellation) for each of the eigenvectors based on the C/I that is given by the eigenvalue. Providing that the channel conditions do not change appreciably in the interval between the time the CSI is measured at the receiver and reported and used to precondition the transmission at the transmitter, the performance of the communications system will then be equivalent to that of a set of independent AWGN channels with known C/I's.

As an example, assume that the MIMO communications mode is applied to a channel data stream that is transmitted on one particular sub-channel from four transmit antennas. The channel data stream is demultiplexed into four data sub-streams, one data sub-stream for each transmit antenna. Each data sub-stream is then modulated using a particular modulation scheme (e.g., M-PSK, M-QAM, or other) selected based on the CSI for that sub-band and for that transmit antenna. Four modulation sub-streams are thus generated for the four data sub-streams, with each modulation sub-streams including a stream of modulation symbols. The four modulation sub-streams are then pre-conditioned using the eigenvector matrix, as expressed above in equation (1), to generate pre-conditioned modulation symbols. The four streams of pre-conditioned modulation symbols are respectively provided to the four combiners of the four transmit antennas. Each combiner combines the received pre-conditioned modulation symbols with the modulation symbols for the other sub-channels to generate a modulation symbol vector stream for the associated transmit antenna.

The full-CSI based processing is typically employed in the MIMO communications mode where parallel data streams are transmitted to a specific user on each of the channel eigenmodes for the each of the allocated sub-channels. Similar processing based on full CSI can be performed where transmission on only a subset of the available eigenmodes is accommodated in each of the allocated sub-channels(e.g., to implement beam steering). Because of the cost associated with the full-CSI processing (e.g., increased complexity at the transmitter and receiver units, increased overhead for the transmission of the CSI from the receiver unit to the transmitter unit, and so on), full-CSI processing can be applied in certain instances in the MIMO communications mode where the additional increase in performance and efficiency is justified.

In instances where full CSI is not available, less descriptive information on the transmission path (or partial CSI) may be available and can be used to pre-condition the data prior to transmission. For example, the C/I of each of the sub-channels may be available. The C/I information can then be used to control the transmission from various transmit antennas to provide the required performance in the sub-channels of interest and increase system capacity.

As used herein, full-CSI based processing modes denote processing modes that use full CSI, and partial-CSI based processing modes denote processing modes that use partial CSI. The full-CSI based processing modes include, for example, the full-CSI MIMO mode that utilizes full-CSI based processing in the MIMO communications mode. The partial-CSI based modes include, for example, the partial-CSI MIMO mode that utilizes partial-CSI based processing in the MIMO communications mode.

In instances where full-CSI or partial-CSI processing is employed to allow the transmitter unit to pre-condition the data using the available channel state information (e.g., the eigenmodes or C/I), feedback information from the receiver unit is required, which uses a portion of the reverse link capacity. Therefore, there is a cost associated with the full-CSI and the partial-CSI based processing modes. The cost should to be factored into the choice of which processing mode to employ. The partial-CSI based processing mode requires less overhead and may be more efficient in some instances. The no-CSI based processing mode requires no overhead and may also be more efficient than the full-CSI based processing mode or the partial-CSI based processing mode under some other circumstances.

If the transmitter unit has CSI and uses the eigenmodes representative of the characteristics of the communications links to transmit independent channel data streams, then the sub-channels allocated in this case are typically uniquely assigned to a single user. On the other hand, if the modulation and coding scheme employed is common for all users (i.e. th CSI employed at the transmitter is not user-specific), then it is possible that information transmitted in this processing mode could be received and decoded by more than one user, depending on their C/I.

FIG. 2 is a diagram that graphically illustrates at least some of the aspects of the communications system of the invention. FIG. 2 shows a specific example of a transmission from one of N_T transmit antennas at a transmitter unit. In FIG. 2, the horizontal axis is time and the vertical axis is frequency. In this example, the transmission channel includes 16 sub-

channels and is used to transmit a sequence of OFDM symbols, with each OFDM symbol covering all 16 sub-channels (one OFDM symbol is indicated at the top of FIG. 2 and includes all 16 sub-bands). A TDM structure is also illustrated in which the data transmission is partitioned into time slots, with each time slot having the duration of, for example, the length of one modulation symbol (i.e., each modulation symbol is used as the TDM interval).

The available sub-channels can be used to transmit signaling, voice, traffic data, and others. In the example shown in FIG. 2, the modulation symbol at time slot 1 corresponds to pilot data, which is periodically transmitted to assist the receiver units synchronize and perform channel estimation. Other techniques for distributing pilot data over time and frequency can also be used and are within the scope of the present invention. In addition, it may be advantageous to utilize a particular modulation scheme during the pilot interval if all sub-channels are employed (e.g., a PN code with a chip duration of approximately 1/W). Transmission of the pilot modulation symbol typically occurs at a particular frame rate, which is usually selected to be fast enough to permit accurate tracking of variations in the communications link.

The time slots not used for pilot transmissions can then be used to transmit various types of data. For example, sub-channels 1 and 2 may be reserved for the transmission of control and broadcast data to the receiver units. The data on these sub-channels is generally intended to be received by all receiver units. However, some of the messages on the control channel may be user specific, and can be encoded accordingly.

Voice data and traffic data can be transmitted in the remaining sub-channels. For the example shown in FIG. 2, sub-channel 3 at time slots 2 through 9 is used for voice call 1, sub-channel 4 at time slots 2 through 9 is used for voice call 2, sub-channel 5 at time slots 5 through 9 is used for voice call 3, and sub-channel 6 at time slots 7 through 9 is used for voice call 5.

The remaining available sub-channels and time slots may be used for transmissions of traffic data. In the example shown in FIG. 2, data 1 transmission uses sub-channels 5 through 16 at time slot 2 and sub-channels 7 through 16 at time slot 7, data 2 transmission uses sub-channels 5 through 16 at time slots 3 and 4 and sub-channels 6 through 16 at time slots 5, data 3 transmission uses sub-channels 6 through 16 at time slot 6, data 4 transmission uses sub-channels 7 through 16 at time slot 8, data 5 transmission uses sub-channels 7 through 11 at time slot 9, and data 6

transmission uses sub-channels 12 through 16 at time slot 9. Data 1 through 6 transmissions can represent transmissions of traffic data to one or more receiver units.

The communications system of the invention flexibly supports the transmissions of traffic data. As shown in FIG. 2, a particular data transmission (e.g., data 2) may occur over multiple sub-channels and/or multiple time slots, and multiple data transmissions (e.g., data 5 and 6) may occur at one time slot. A data transmission (e.g., data 1) may also occur over non-contiguous time slots. The system can also be designed to support multiple data transmissions on one sub-channel. For example, voice data may be multiplexed with traffic data and transmitted on a single sub-channel.

The multiplexing of the data transmissions can potentially change from OFDM symbol to symbol. Moreover, the communications mode may be different from user to user (e.g., from one voice or data transmission to other). For example, the voice users may use the diversity communications mode, and the data users may use the MIMO communications modes. These features concept can be extended to the sub-channel level. For example, a data user may use the MIMO communications mode in sub-channels that have sufficient C/I and the diversity communications mode in remaining sub-channels.

Antenna, frequency, and temporal diversity may be respectively achieved by transmitting data from multiple antennas, on multiple sub-channels in different sub-bands, and over multiple time slots. For example, antenna diversity for a particular transmission (e.g., voice call 1) may be achieved by transmitting the (voice) data on a particular sub-channel (e.g., sub-channel 1) over two or more antennas. Frequency diversity for a particular transmission (e.g., voice call 1) may be achieved by transmitting the data on two or more sub-channels in different sub-bands (e.g., sub-channels 1 and 2). A combination of antenna and frequency diversity may be obtained by transmitting data from two or more antennas and on two or more sub-channels. Temporal diversity may be achieved by transmitting data over multiple time slots. For example, as shown in FIG. 2, data 1 transmission at time slot 7 is a portion (e.g., new or repeated) of the data 1 transmission at time slot 2.

The same or different data may be transmitted from multiple antennas and/or on multiple sub-bands to obtain the desired diversity. For example, the data may be transmitted on: (1) one sub-channel from one

antenna, (2) one sub-channel (e.g., sub-channel 1) from multiple antennas, (3) one sub-channel from all N_T antennas, (4) a set of sub-channels (e.g., sub-channels 1 and 2) from one antenna, (5), a set of sub-channels from multiple antennas, (6) a set of sub-channels from all N_T antennas, or (7) a set of channels from a set of antennas (e.g., sub-channel 1 from antennas 1 and 2 at one time slot, sub-channels 1 and 2 from antenna 2 at another time slot, and so on). Thus, any combination of sub-channels and antennas may be used to provide antenna and frequency diversity.

In accordance with certain embodiments of the invention that provide the most flexibility and are capable of achieving high performance and efficiency, each sub-channel at each time slot for each transmit antenna may be viewed as an independent unit of transmission (i.e., a modulation symbol) that can be used to transmit any type of data such as pilot, signaling, broadcast, voice, traffic data, and others, or a combination thereof (e.g., multiplexed voice and traffic data). In such design, a voice call may be dynamically assigned different sub-channels over time.

Flexibility, performance, and efficiency are further achieved by allowing for independence among the modulation symbols, as described below. For example, each modulation symbol may be generated from a modulation scheme (e.g., M-PSK, M-QAM, and others) that results in the best use of the resource at that particular time, frequency, and space.

A number of constraints may be placed to simplify the design and implementation of the transmitter and receiver units. For example, a voice call may be assigned to a particular sub-channel for the duration of the call, or until such time as a sub-channel reassignment is performed. Also, signaling and/or broadcast data may be designated to some fixed sub-channels (e.g., sub-channel 1 for control data and sub-channel 2 for broadcast data, as shown FIG. 2) so that the receiver units know a priori which sub-channels to demodulate to receive the data.

Also, each data transmission channel or sub-channel may be restricted to a particular modulation scheme (e.g., M-PSK, M-QAM) for the duration of the transmission or until such time as a new modulation scheme is assigned. For example, in FIG. 2, voice call 1 on sub-channel 3 may use QPSK, voice call 2 on sub-channel 4 may use 16-QAM, data 1 transmission at time slot 2 may use 8-PSK, data 2 transmission at time slots 3 through 5 may use 16-QAM, and so on.

The use of TDM allows for greater flexibility in the transmission of voice data and traffic data, and various assignments of resources can be

contemplated. For example, a user can be assigned one sub-channel for each time slot or, equivalently, four sub-channels every fourth time slot, or some other allocations. TDM allows for data to be aggregated and transmitted at designated time slot(s) for improved efficiency.

If voice activity is implemented at the transmitter, then in the intervals where no voice is being transmitted, the transmitter may assign other users to the sub-channel so that the sub-channel efficiency is maximized. In the event that no data is available to transmit during the idle voice periods, the transmitter can decrease (or turn-off) the power transmitted in the sub-channel, reducing the interference levels presented to other users in the system that are using the same sub-channel in another cell in the network. The same feature can be also extended to the overhead, control, data, and other channels.

Allocation of a small portion of the available resources over a continuous time period typically results in lower delays, and may be better suited for delay sensitive services such as voice. Transmission using TDM can provide higher efficiency, at the cost of possible additional delays. The communications system of the invention can allocate resources to satisfy user requirements and achieve high efficiency and performance.

FIG. 3 is a block diagram of an embodiment of data processor 112 and modulator 114 of system 110 in FIG. 1. The aggregate input data stream that includes all data to be transmitted by system 110 is provided to a demultiplexer (DEMUX) 310 within data processor 112. Demultiplexer 310 demultiplexes the input data stream into a number of (K) channel data stream, S_1 through S_k. Each channel data stream may correspond to, for example, a signaling channel, a broadcast channel, a voice call, or a traffic data transmission. Each channel data stream is provided to a respective encoder 312 that encodes the data using a particular encoding scheme.

The encoding may include error correction coding or error detection coding, or both, used to increase the reliability of the link. More specifically, such encoding may include, for example, interleaving, convolutional coding, Turbo coding, Trellis coding, block coding (e.g., Reed-Solomon coding), cyclic redundancy check (CRC) coding, and others. Turbo encoding is described in further detail in U.S. Patent Application Serial No. 09/205,511, filed December 4, 1998 entitled "Turbo Code Interleaver Using Linear Congruential Sequences" and in a document entitled "The cdma2000 ITU-R RTT Candidate Submission," hereinafter referred to as the IS-2000 standard, both of which are incorporated herein by reference.

The encoding can be performed on a per channel basis, i.e., on each channel data stream, as shown in FIG. 3. However, the encoding may also be performed on the aggregate input data stream, on a number of channel data streams, on a portion of a channel data stream, across a set of antennas, across a set of sub-channels, across a set of sub-channels and antennas, across each sub-channel, on each modulation symbol, or on some other unit of time, space, and frequency. The encoded data from encoders 312a through 312k is then provided to a data processor 320 that processes the data to generate modulation symbols.

In one implementation, data processor 320 assigns each channel data stream to one or more sub-channels, at one or more time slots, and on one or more antennas. For example, for a channel data stream corresponding to a voice call, data processor 320 may assign one sub-channel on one antenna (if transmit diversity is not used) or multiple antennas (if transmit diversity is used) for as many time slots as needed for that call. For a channel data stream corresponding to a signaling or broadcast channel, data processor 320 may assign the designated sub-channel(s) on one or more antennas, again depending on whether transmit diversity is used. Data processor 320 then assigns the remaining available resources for channel data streams corresponding to data transmissions. Because of the burstiness nature of data transmissions and the greater tolerance to delays, data processor 320 can assign the available resources such that the system goals of high performance and high efficiency are achieved. The data transmissions are thus "scheduled" to achieve the system goals.

After assigning each channel data stream to its respective time slot(s), sub-channel(s), and antenna(s), the data in the channel data stream is modulated using multi-carrier modulation. In an embodiment, OFDM modulation is used to provide numerous advantages. In one implementation of OFDM modulation, the data in each channel data stream is grouped to blocks, with each block having a particular number of data bits. The data bits in each block are then assigned to one or more sub-channels associated with that channel data stream.

The bits in each block are then demultiplexed into separate sub-channels, with each of the sub-channels conveying a potentially different number of bits (i.e., based on C/I of the sub-channel and whether MIMO processing is employed). For each of these sub-channels, the bits are grouped into modulation symbols using a particular modulation scheme (e.g., M-PSK or M-QAM) associated with that sub-channel. For example,

with 16-QAM, the signal constellation is composed of 16 points in a complex plane (i.e., a + j*b), with each point in the complex plane conveying 4 bits of information. In the MIMO processing mode, each modulation symbol in the sub-channel represents a linear combination of modulation symbols, each of which may be selected from a different constellation.

The collection of L modulation symbols form a modulation symbol vector V of dimensionality L. Each element of the modulation symbol vector V is associated with a specific sub-channel having a unique frequency or tone on which the modulation symbols is conveyed. The collection of these L modulation symbols are all orthogonal to one another. At each time slot and for each antenna, the L modulation symbols corresponding to the L sub-channels are combined into an OFDM symbol using an inverse fast Fourier transform (IFFT). Each OFDM symbol includes data from the channel data streams assigned to the L sub-channels.

OFDM modulation is described in further detail in a paper entitled "Multicarrier Modulation for Data Transmission : An Idea Whose Time Has Come," by John A.C. Bingham, IEEE Communications Magazine, May 1990, which is incorporated herein by reference.

Data processor 320 thus receives and processes the encoded data corresponding to K channel data streams to provide N_T modulation symbol vectors, V_1 through V_{NT}, one modulation symbol vector for each transmit antenna. In some implementations, some of the modulation symbol vectors may have duplicate information on specific sub-channels intended for different transmit antennas. The modulation symbol vectors V_1 through V_{NT} are provided to modulators 114a through 114t, respectively.

In the embodiment shown in FIG. 3, each modulator 114 includes an IFFT 330, cycle prefix generator 332, and an upconverter 334. IFFT 330 converts the received modulation symbol vectors into their time-domain representations called OFDM symbols. IFFT 330 can be designed to perform the IFFT on any number of sub-channels (e.g., 8, 16, 32, and so on). In an embodiment, for each modulation symbol vector converted to an OFDM symbol, cycle prefix generator 332 repeats a portion of the time-domain representation of the OFDM symbol to form the transmission symbol for the specific antenna. The cyclic prefix insures that the transmission symbol retains its orthogonal properties in the presence of multipath delay spread, thereby improving performance against deleterious path effects, as described below. The implementation of IFFT 330 and cycle prefix generator 332 is known in the art and not described in detail herein.

The time-domain representations from each cycle prefix generator 332 (i.e., the transmission symbols for each antenna) are then processed by upconverter 332, converted into an analog signal, modulated to a RF frequency, and conditioned (e.g., amplified and filtered) to generate an RF modulated signal that is then transmitted from the respective antenna 116.

FIG. 3 also shows a block diagram of an embodiment of data processor 320. The encoded data for each channel data stream (i.e., the encoded data stream, X) is provided to a respective channel data processor 332. If the channel data stream is to be transmitted over multiple sub-channels and/or multiple antennas (without duplication on at least some of the transmissions), channel data processor 332 demultiplexes the channel data stream into a number of (up to $L \bullet N_T$) data sub-streams. Each data sub-stream corresponds to a transmission on a particular sub-channel at a particular antenna. In typical implementations, the number of data sub-streams is less than $L \bullet N_T$ since some of the sub-channels are used for signaling, voice, and other types of data. The data sub-streams are then processed to generate corresponding sub-streams for each of the assigned sub-channels that are then provided to combiners 334. Combiners 334 combine the modulation symbols designated for each antenna into modulation symbol vectors that are then provided as a modulation symbol vector stream. The N_T modulation symbol vector streams for the N_T antennas are then provided to the subsequent processing blocks (i.e., modulators 114).

In a design that provides the most flexibility, best performance, and highest efficiency, the modulation symbol to be transmitted at each time slot, on each sub-channel, can be individually and independently selected. This feature allows for the best use of the available resource over all three dimensions - time, frequency, and space. The number of data bits transmitted by each modulation symbol may thus differ.

FIG. 4A is a block diagram of an embodiment of a channel data processor 400 that can be used for processing one channel data steam. Channel data processor 400 can be used to implement one channel data processor 332 in FIG. 3. The transmission of a channel data stream may occur on multiple sub-channels (e.g., as for data 1 in FIG. 2) and may also occur from multiple antennas. The transmission on each sub-channel and from each antenna can represent non-duplicated data.

Within channel data processor 400, a demultiplexer 420 receives and demultiplexes the encoded data stream, X_i, into a number of sub-channel

data streams, $X_{i,1}$ through $X_{i,M}$, one sub-channel data stream for each sub-channel being used to transmit data. The data demultiplexing can be uniform or non-uniform. For example, if some information about the transmission paths is known (i.e., full CSI or partial CSI is known), demultiplexer 420 may direct more data bits to the sub-channels capable of transmitting more bps/Hz. However, if no CSI is known, demultiplexer 420 may uniformly directs approximately equal number of bits to each of the allocated sub-channels.

Each sub-channel data stream is then provided to a respective spatial division processor 430. Each spatial division processor 430 may further demultiplex the received sub-channel data stream into a number of (up to N_T) data sub-streams, one data sub-stream for each antenna used to transmit the data. Thus, after demultiplexer 420 and spatial division processor 430, the encoded data stream X_i may be demultiplexed into up to $L \bullet N_T$ data sub-streams to be transmitted on up to L sub-channels from up to N_T antennas.

At any particular time slot, up to N_T modulation symbols may be generated by each spatial division processor 430 and provided to N_T combiners 400a through 440t. For example, spatial division processor 430a assigned to sub-channel 1 may provide up to N_T modulation symbols for sub-channel 1 of antennas 1 through N_T. Similarly, spatial division processor 430k assigned to sub-channel k may provide up to N_T symbols for sub-channel k of antennas 1 through N_T. Each combiner 440 receives the modulation symbols for the L sub-channels, combines the symbols for each time slot into a modulation symbol vector, and provides the modulation symbol vectors as a modulation symbol vector stream, V, to the next processing stage (e.g., modulator 114).

Channel data processor 400 may also be designed to provide the necessary processing to implement the full-CSI or partial-CSI processing modes described above. The CSI processing may be performed based on the available CSI information and on selected channel data streams, sub-channels, antennas, etc. The CSI processing may also be enabled and disabled selectively and dynamically. For example, the CSI processing may be enabled for a particular transmission and disabled for some other transmissions. The CSI processing may be enabled under certain conditions, for example, when the transmission link has adequate C/I.

Channel data processor 400 in FIG. 4A provides a high level of flexibility. However, such flexibility is typically not needed for all channel data streams. For example, the data for a voice call is typically transmitted

over one sub-channel for the duration of the call, or until such time as the sub-channel is reassigned. The design of the channel data processor can be greatly simplified for these channel data streams.

FIG. 4B is a block diagram of the processing that can be employed for one channel data steam such as overhead data, signaling, voice, or traffic data. A spatial division processor 450 can be used to implement one channel data processor 332 in FIG. 3 and can be used to support a channel data stream such as, for example, a voice call. A voice call is typically assigned to one sub-channel for multiple time slots (e.g., voice 1 in FIG. 2) and may be transmitted from multiple antennas. The encoded data stream, X_j, is provided to spatial division processor 450 that groups the data into blocks, with each block having a particular number of bits that are used to generate a modulation symbol. The modulation symbols from spatial division processor 450 are then provided to one or more combiners 440 associated with the one or more antennas used to transmit the channel data stream.

A specific implementation of a transmitter unit capable of generating the transmit signal shown in FIG. 2 is now described for a better understanding of the invention. At time slot 2 in FIG. 2, control data is transmitted on sub-channel 1, broadcast data is transmitted on sub-channel 2, voice calls 1 and 2 are assigned to sub-channels 3 and 4, respectively, and traffic data is transmitted on sub-channels 5 through 16. In this example, the transmitter unit is assumed to include four transmit antennas (i.e., $N_T = 4$) and four transmit signals (i.e., four RF modulated signals) are generated for the four antennas.

FIG. 5A is a block diagram of a portion of the processing units that can be used to generate the transmit signal for time slot 2 in FIG. 2. The input data stream is provided to a demultiplexer (DEMUX) 510 that demultiplexes the stream into five channel data streams, S_1 through S_5, corresponding to control, broadcast, voice 1, voice 2, and data 1 in FIG. 2. Each channel data stream is provided to a respective encoder 512 that encodes the data using an encoding scheme selected for that stream.

In this example, channel data streams S_1 through S_3 are transmitted using transmit diversity. Thus, each of the encoded data streams X_1 through X_3 is provided to a respective channel data processor 532 that generates the modulation symbols for that stream. The modulation symbols from each of the channel data processors 532a through 532c are then provided to all four combiners 540a through 540d. Each combiner 540 receives the modulation

symbols for all 16 sub-channels designated for the antenna associated with the combiner, combines the symbols on each sub-channel at each time slot to generate a modulation symbol vector, and provides the modulation symbol vectors as a modulation symbol vector stream, V, to an associated modulator 114. As indicated in FIG. 5A, channel data stream S_1 is transmitted on sub-channel 1 from all four antennas, channel data stream S_2 is transmitted on sub-channel 2 from all four antennas, and channel data stream S_3 is transmitted on sub-channel 3 from all four antennas.

FIG. 5B is a block diagram of a portion of the processing units used to process the encoded data for channel data stream S_4. In this example, channel data stream S_4 is transmitted using spatial diversity (and not transmit diversity as used for channel data streams S_1 through S_3). With spatial diversity, data is demultiplexed and transmitted (concurrently in each of the assigned sub-channels or over different time slots) over multiple antennas. The encoded data stream X_4 is provided to a channel data processor 532d that generates the modulation symbols for that stream. The modulation symbols in this case are linear combinations of modulation symbols selected from symbol alphabets that correspond to each of the eigenmodes of the channel. In this example, there are four distinct eigenmodes, each of which is capable of conveying a different amount of information. As an example, suppose eigenmode 1 has a C/I that allows 64-QAM (6 bits) to be transmitted reliably, eigenmode 2 permits 16-QAM (4 bits), eigenmode 3 permits QPSK (2 bits) and eigenmode 4 permits BPSK (1 bit) to be used. Thus, the combination of all four eigenmodes allows a total of 13 information bits to be transmitted simultaneously as an effective modulation symbol on all four antennas in the same sub-channel. The effective modulation symbol for the assigned sub-channel on each antenna is a linear combination of the individual symbols associated with each eigenmode, as described by the matrix multiply given in equation (1) above.

FIG. 5C is a block diagram of a portion of the processing units used to process channel data stream S_5. The encoded data stream X_5 is provided to a demultiplexer (DEMUX) 530 that demultiplexes the stream X_5 into twelve sub-channel data streams, $X_{5,11}$ through $X_{5,16}$, one sub-channel data stream for each of the allocated sub-channels 5 through 16. Each sub-channel data stream is then provided to a respective sub-channel data processor 536 that generates the modulation symbols for the associated sub-channel data stream. The sub-channel symbol stream from sub-channel data processors 536a through 536l are then provided to demultiplexers 538a through 538l,

respectively. Each demultiplexer 538 demultiplexes the received sub-channel symbol stream into four symbol sub-streams, with each symbol sub-stream corresponding to a particular sub-channel at a particular antenna. The four symbol sub-streams from each demultiplexer 538 are then provided to the four combiners 540a through 540d.

In the embodiment described for FIG. 5C, a sub-channel data stream is processed to generate a sub-channel symbol stream that is then demultiplexed into four symbol sub-streams, one symbol sub-stream for a particular sub-channel of each antenna. This implementation is a different from that described for FIG. 4A. In the embodiment described for FIG. 4A, the sub-channel data stream designated for a particular sub-channel is demultiplexed into a number of data sub-streams, one data sub-stream for each antenna, and then processed to generate the corresponding symbol sub-streams. The demultiplexing in FIG. 5C is performed after the symbol modulation whereas the demultiplexing in FIG. 4A is performed before the symbol modulation. Other implementations may also be used and are within the scope of the present invention.

Each combination of sub-channel data processor 536 and demultiplexer 538 in FIG. 5C performs in similar manner as the combination of sub-channel data processor 532d and demultiplexer 534d in FIG. 5B. The rate of each symbol sub-stream from each demultiplexer 538 is, on the average, a quarter of the rate of the symbol stream from the associated channel data processor 536.

FIG. 6 is a block diagram of an embodiment of a receiver unit 600, having multiple receive antennas, which can be used to receive one or more channel data streams. One or more transmitted signals from one or more transmit antennas can be received by each of antennas 610a through 610r and routed to a respective front end processor 612. For example, receive antenna 610a may receive a number of transmitted signals from a number of transmit antennas, and receive antenna 610r may similarly receive multiple transmitted signals. Each front end processor 612 conditions (e.g., filters and amplifies) the received signal, downconverts the conditioned signal to an intermediate frequency or baseband, and samples and quantizes the downconverted signal. Each front end processor 612 typically further demodulates the samples associated with the specific antenna with the received pilot to generate "coherent" samples that are then provided to a respective FFT processor 614, one for each receive antenna.

Each FFT processor 614 generates transformed representations of the received samples and provides a respective stream of modulation symbol vectors. The modulation symbol vector streams from FFT processors 614a through 614r are then provided to demultiplexer and combiners 620, which channelizes the stream of modulation symbol vectors from each FFT processor 614 into a number of (up to L) sub-channel symbol streams. The sub-channel symbol streams from all FFT processors 614 are then processed, based on the (e.g., diversity or MIMO) communications mode used, prior to demodulation and decoding.

For a channel data stream transmitted using the diversity communications mode, the sub-channel symbol streams from all antennas used for the transmission of the channel data stream are presented to a combiner that combines the redundant information across time, space, and frequency. The stream of combined modulation symbols are then provided to a (diversity) channel processor 630 and demodulated accordingly.

For a channel data stream transmitted using the MIMO communications mode, all sub-channel symbol streams used for the transmission of the channel data stream are presented to a MIMO processor that orthogonalizes the received modulation symbols in each sub-channel into the distinct eigenmodes. The MIMO processor performs the processing described by equation (2) above and generates a number of independent symbol sub-streams corresponding to the number of eigenmodes used at the transmitter unit. For example, MIMO processor can perform multiplication of the received modulation symbols with the left eigenvectors to generate post-conditioned modulation symbols, which correspond to the modulation symbols prior to the full-CSI processor at the transmitter unit. The (post-conditioned) symbol sub-streams are then provided to a (MIMO) channel processor 630 and demodulated accordingly. Thus, each channel processor 630 receives a stream of modulation symbols (for the diversity communications mode) or a number of symbol sub-streams (for the MIMO communications mode). Each stream or sub-stream of modulation symbols is then provided to a respective demodulator (DEMOD) that implements a demodulation scheme (e.g., M-PSK, M-QAM, or others) that is complementary to the modulation scheme used at the transmitter unit for the sub-channel being processed. For the MIMO communications mode, the demodulated data from all assigned demodulators may then be decoded independently or multiplexed into one channel data stream and then decoded, depending upon the coding and modulation method employed at

the transmitter unit. For both the diversity and MIMO communications modes, the channel data stream from channel processor 630 may then provided to a respective decoder 640 that implements a decoding scheme complementary to that used at the transmitter unit for the channel data stream. The decoded data from each decoder 540 represents an estimate of the transmitted data for that channel data stream.

FIG. 6 represents one embodiment of a receiver unit. Other designs can contemplated and are within the scope of the present invention. For example, a receiver unit may be designed with only one receive antenna, or may be designed capable of simultaneous processing multiple (e.g., voice, data) channel data streams.

As noted above, multi-carrier modulation is used in the communications system of the invention. In particular, OFDM modulation can be employed to provide a number of benefits including improved performance in a multipath environment, reduced implementation complexity (in a relative sense, for the MIMO mode of operation), and flexibility. However, other variants of multi-carrier modulation can also be used and are within the scope of the present invention.

OFDM modulation can improve system performance due to multipath delay spread or differential path delay introduced by the propagation environment between the transmitting antenna and the receiver antenna. The communications link (i.e., the RF channel) has a delay spread that may potentially be greater than the reciprocal of the system operating bandwidth, W. Because of this, a communications system employing a modulation scheme that has a transmit symbol duration of less than the delay spread will experience inter-symbol interference (ISI). The ISI distorts the received symbol and increases the likelihood of incorrect detection.

With OFDM modulation, the transmission channel (or operating bandwidth) is essentially divided into a (large) number of parallel sub-channels (or sub-bands) that are used to communicate the data. Because each of the sub-channels has a bandwidth that is typically much less than the coherence bandwidth of the communications link, ISI due to delay spread in the link is significantly reduced or eliminated using OFDM modulation. In contrast, most conventional modulation schemes (e.g., QPSK) are sensitive to ISI unless the transmission symbol rate is small compared to the delay spread of the communications link.

As noted above, cyclic prefix can be used to combat the deleterious effects of multipath. A cyclic prefix is a portion of an OFDM symbol (usually the front portion, after the IFFT) that is wrapped around to the back of the symbol. The cyclic prefix is used to retain orthogonality of the OFDM symbol, which is typically destroyed by multipath.

As an example, consider a communications system in which the channel delay spread is less than 10 μsec. Each OFDM symbol has appended onto it a cyclic prefix that insures that the overall symbol retains its orthogonal properties in the presence of multipath delay spread. Since the cyclic prefix conveys no additional information, it is essentially overhead. To maintain good efficiency, the duration of the cyclic prefix is selected to be a small fraction of the overall transmission symbol duration. For the above example, using a 5% overhead to account for the cyclic prefix, an transmission symbol duration of 200 μsec is adequate for a 10 μsec maximum channel delay spread. The 200 μsec transmission symbol duration corresponds to a bandwidth of 5 kHz for each of the sub-bands. If the overall system bandwidth is 1.2288 MHz, 250 sub-channels of approximately 5 kHz can be provided. In practice, it is convenient for the number of sub-channels to be a power of two. Thus, if the transmission symbol duration is increased to 205 μsec and the system bandwidth is divided into $M = 256$ sub-bands, each sub-channel will have a bandwidth of 4.88 kHz.

In certain embodiments of the invention, OFDM modulation can reduce the complexity of the system. When the communications system incorporates MIMO technology, the complexity associated with the receiver unit can be significant, particularly when multipath is present. The use of OFDM modulation allows each of the sub-channels to be treated in an independent manner by the MIMO processing employed. Thus, OFDM modulation can significantly simplify the signal processing at the receiver unit when MIMO technology is used.

OFDM modulation can also afford added flexibility in sharing the system bandwidth, W, among multiple users. Specifically, the available transmission space for OFDM symbols can be shared among a group of users. For example, low rate voice users can be allocated a sub-channel or a fraction of a sub-channel in OFDM symbol, while the remaining sub-channels can be allocated to data users based on aggregate demand. In addition, overhead, broadcast, and control data can be conveyed in some of the available sub-channels or (possibly) in a portion of a sub-channel.

As described above, each sub-channel at each time slot is associated with a modulation symbol that is selected from some alphabet such as M-PSK or M-QAM. In certain embodiments, the modulation symbol in each of the L sub-channels can be selected such that the most efficient use is made of that sub-channel. For example, sub-channel 1 can be generated using QPSK, sub-channel 2 can be generate using BPSK, sub-channel 3 can be generated using 16-QAM, and so on. Thus, for each time slot, up to L modulation symbols for the L sub-channels are generated and combined to generate the modulation symbol vector for that time slot.

One or more sub-channels can be allocated to one or more users. For example, each voice user may be allocated a single sub-channel. The remaining sub-channels can be dynamically allocated to data users. In this case, the remaining sub-channels can be allocated to a single data user or divided among multiple data users. In addition, some sub-channels can be reserved for transmitting overhead, broadcast, and control data. In certain embodiments of the invention, it may be desirable to change the sub-channel assignment from (possibly) modulation symbol to symbol in a pseudo-random manner to increase diversity and provide some interference averaging.

In a CDMA system, the transmit power on each reverse link transmission is controlled such that the required frame error rate (FER) is achieved at the base station at the minimal transmit power, thereby minimizing interference to other users in the system. On the forward link of the CDMA system, the transmit power is also adjusted to increase system capacity.

In the communications system of the invention, the transmit power on the forward and reverse links can be controlled to minimize interference and maximize system capacity. Power control can be achieved in various manners. For example, power control can be performed on each channel data stream, on each sub-channel, on each antenna, or on some other unit of measurements. When operating in the diversity communications mode, if the path loss from a particular antenna is great, transmission from this antenna can be reduced or muted since little may be gained at the receiver unit. Similarly, if transmission occurs over multiple sub-channels, less power may be transmitted on the sub-channel(s) experiencing the most path loss.

In an implementation, power control can be achieved with a feedback mechanism similar to that used in the CDMA system. Power control

information can be sent periodically or autonomously from the receiver unit to the transmitter unit to direct the transmitter unit to increase or decrease its transmit power. The power control bits may be generated based on, for example, the BER or FER at the receiver unit.

FIG. 7 shows plots that illustrate the spectral efficiency associated with some of the communications modes of the communications system of the invention. In FIG. 7, the number of bits per modulation symbol for a given bit error rate is given as a function of C/I for a number of system configurations. The notation N_TxN_R denotes the dimensionality of the configuration, with N_T = number of transmit antennas and N_R = number of receive antennas. Two diversity configurations, namely 1x2 and 1x4, and four MIMO configurations, namely 2x2, 2x4, 4x4, and 8x4, are simulated and the results are provided in FIG. 7.

As shown in the plots, the number of bits per symbol for a given BER ranges from less than 1 bps/Hz to almost 20 bps/Hz. At low values of C/I, the spectral efficiency of the diversity communications mode and MIMO communications mode is similar, and the improvement in efficiency is less noticeable. However, at higher values of C/I, the increase in spectral efficiency with the use of the MIMO communications mode becomes more dramatic. In certain MIMO configurations and for certain conditions, the instantaneous improvement can reach up to 20 times.

From these plots, it can be observed that spectral efficiency generally increases as the number of transmit and receive antennas increases. The improvement is also generally limited to the lower of N_T and N_R. For example, the diversity configurations, 1x2 and 1x4, both asymptotically reach approximately 6 bps/Hz.

In examining the various data rates achievable, the spectral efficiency values given in FIG. 7 can be applied to the results on a sub-channel basis to obtain the range of data rates possible for the sub-channel. As an example, for a subscriber unit operating at a C/I of 5 dB, the spectral efficiency achievable for this subscriber unit is between 1 bps/Hz and 2.25 bps/Hz, depending on the communications mode employed. Thus, in a 5 kHz sub-channel, this subscriber unit can sustain a peak data rate in the range of 5 kbps to 10.5 kbps. If the C/I is 10 dB, the same subscriber unit can sustain peak data rates in the range of 10.5 kbps to 25 kbps per sub-channel. With 256 sub-channels available, the peak sustained data rate for a subscriber unit operating at 10 dB C/I is then 6.4 Mbps. Thus, given the data rate requirements of the subscriber unit and the operating C/I for the subscriber

unit, the system can allocate the necessary number of sub-channels to meet the requirements. In the case of data services, the number of sub-channels allocated per time slot may vary depending on, for example, other traffic loading.

The reverse link of the communications system can be designed similar in structure to the forward link. However, instead of broadcast and common control channels, there may be random access channels defined in specific sub-channels or in specific modulation symbol positions of the frame, or both. These may be used by some or all subscriber units to send short requests (e.g., registration, request for resources, and so on) to the central station. In the common access channels, the subscriber units may employ common modulation and coding. The remaining channels may be allocated to separate users as in the forward link. In an embodiment, allocation and de-allocation of resources (on both the forward and reverse links) are controlled by the system and communicated on the control channel in the forward link.

One design consideration for on the reverse link is the maximum differential propagation delay between the closest subscriber unit and the furthest subscriber unit. In systems where this delay is small relative to the cyclic prefix duration, it may not be necessary to perform correction at the transmitter unit. However, in systems in which the delay is significant, the cyclic prefix can be extended to account for the incremental delay. In some instances, it may be possible to make a reasonable estimate of the round trip delay and correct the time of transmit so that the symbol arrives at the central station at the correct instant. Usually there is some residual error, so the cyclic prefix may also further be extended to accommodate this residual error.

In the communications system, some subscriber units in the coverage area may be able to receive signals from more than one central station. If the information transmitted by multiple central stations is redundant on two or more sub-channels and/or from two or more antennas, the received signals can be combined and demodulated by the subscriber unit using a diversity-combining scheme. If the cyclic prefix employed is sufficient to handle the differential propagation delay between the earliest and latest arrival, the signals can be (optimally) combined in the receiver and demodulated correctly. This diversity reception is well known in broadcast applications of OFDM. When the sub-channels are allocated to specific subscriber units, it is possible for the same information on a specific sub-

channel to be transmitted from a number of central stations to a specific subscriber unit. This concept is similar to the soft handoff used in CDMA systems.

As shown above, the transmitter unit and receiver unit are each implemented with various processing units that include various types of data processor, encoders, IFFTs, FFTs, demultiplexers, combiners, and so on. These processing units can be implemented in various manners such as an application specific integrated circuit (ASIC), a digital signal processor, a microcontroller, a microprocessor, or other electronic circuits designed to perform the functions described herein. Also, the processing units can be implemented with a general-purpose processor or a specially designed processor operated to execute instruction codes that achieve the functions described herein. Thus, the processing units described herein can be implemented using hardware, software, or a combination thereof.

The foregoing description of the preferred embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without the use of the inventive faculty. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

CLAIMS

1. A transmitter unit in a communications system configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals, comprising:

a system data processor operative to receive and partition an input data stream into a plurality of channel data streams and to process the plurality of channel data streams to generate one or more modulation symbol vector streams, wherein each modulation symbol vector stream comprises a sequence of modulation symbol vectors representative of the data in one or more channel data streams, and wherein each modulation symbol vector comprises a plurality of modulation symbols and is generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof;

at least one modulator coupled to the system data processor, the at least one modulator operative to receive and modulate a respective modulation symbol vector stream to provide a modulated signal; and

at least one antenna coupled to the at least one modulator, the at least one antenna operative to receive and transmit a respective modulated signal.

2. The transmitter unit of claim 1, wherein the system data processor includes

at least one channel data processor, each channel data processor operative to receive and process a respective channel data stream to generate a stream of modulation symbols.

3. The transmitter unit of claim 2, wherein the system data processor further includes

at least one encoder, each encoder operative to receive and encode a respective channel data stream to generate an encoded data stream, and

wherein each channel data processor is operative to receive and process a respective encoded data stream.

4. The transmitter unit of claim 2, wherein the system data processor further includes

at least one demultiplexer, each demultiplexer coupled to a respective channel data processor and operative to receive and demultiplex the stream

of modulation symbols into one or more symbol sub-streams, one symbol sub-stream for each antenna.

5. The transmitter unit of claim 2, wherein the system data processor further includes

at least one combiner, one combiner for each antenna, each combiner coupled to the at least one channel data processor and operative to receive and selectively combine at least one stream of modulation symbols from the at least one channel data processor to generate a respective modulation symbol vector stream.

6. The transmitter unit of claim 1, wherein each modulator includes

an inverse Fourier transform operative to receive a respective modulation symbol vector stream and generate a time-domain representation of the modulation symbol vector stream.

7. The transmitter unit of claim 6, wherein each modulator further includes

a cyclic prefix generator coupled to the inverse Fourier transform and operative to repeat a portion of the time-domain representation of each modulation symbol vector.

8. The transmitter unit of claim 1, wherein the system data processor is operative to modulate the plurality of channel data streams using multi-carrier modulation to generate the one or more symbol vector streams.

9. The transmitter unit of claim 8, wherein the multi-carrier modulation is orthogonal frequency division multiplexing (OFDM) modulation.

10. The transmitter unit of claim 8, wherein the multi-carrier modulation partitions a total operating bandwidth of the communications system into a plurality of (L) sub-bands, wherein each sub-band is associated with a different center frequency and corresponds to one sub-channel.

11. The transmitter unit of claim 8, wherein data on each channel data stream is modulated with a particular modulation scheme selected from a set that includes M-PSK and M-QAM.

12. The transmitter unit of claim 8, wherein data to be transmitted on each sub-channel is modulated with a particular modulation scheme selected from a set that includes M-PSK and M-QAM.

13. The transmitter unit of claim 10, wherein L is 64 or greater.

14. The transmitter unit of claim 10, wherein L is 256 or greater.

15. The transmitter unit of claim 1, wherein the modulation symbol vectors in the modulation symbol vector stream are orthogonal frequency division multiplexing (OFDM) symbols.

16. The transmitter unit of claim 1, wherein at least one channel data stream is processed using a diversity communications mode characterized by transmission of each of the at least one channel data stream on one or more sub-channels, from one or more antennas, or at one or more time periods, or a combination thereof, to improve the reliability of the transmission.

17. The transmitter unit of claim 1, wherein use of the diversity communications mode is based, in part, on a quality of one or more communications links used for a particular channel data stream transmission.

18. The transmitter unit of claim 1, wherein at least one channel data stream is processed using a MIMO communications mode characterized by transmission of each of the at least one channel data stream using a plurality of transmit antennas and reception of the transmission using a plurality of receive antennas to improve the reliability of the transmission and increase link capacity.

19. The transmitter unit of claim 1, wherein at least one channel data stream is processed using a diversity communications mode and at least one other channel data stream is processed using a MIMO communications mode, wherein the diversity communications mode is characterized by transmission of a channel data stream on one or more sub-channels, from one or more antennas, or at one or more time periods, or a combination

thereof, to improve the reliability of the transmission, and wherein the MIMO communications mode characterized by transmission of a channel data stream using a plurality of transmit antennas and reception of the transmission using a plurality of receive antennas to improve the reliability of the transmission and increase link capacity.

20. The transmitter unit of claim 1, wherein the system data processor is further operative to pre-condition the modulation symbols in accordance with channel state information (CSI) descriptive of characteristics of one or more communications links used to transmit the one or more modulated signals.

21. The transmitter unit of claim 20, wherein the CSI includes carrier-to-noise-plus-interference ratio (C/I) values for the one or more communications links.

22. The transmitter unit of claim 20, wherein the CSI is defined by a matrix corresponding to the one or more communications links.

23. The transmitter unit of claim 1, wherein at least one channel data stream is transmitted over two or more antennas, concurrently or at different times, to provide antenna diversity.

24. The transmitter unit of claim 1, wherein at least a portion of at least one channel data stream is redundantly transmitted over two or more antennas to provide transmit diversity.

25. The transmitter unit of claim 1, wherein at least a portion of at least one channel data stream is transmitted over two or more time periods to provide temporal diversity.

26. The transmitter unit of claim 10, wherein at least a portion of at least one channel data stream is transmitted on two or more sub-bands to provide frequency diversity.

27. The transmitter unit of claim 1, wherein the plurality of channel data streams are transmitted in time division multiplexed (TDM) time slots.

28. The transmitter unit of claim 27, wherein the each time slot has a duration that is related to a length of one modulation symbol.

29. The transmitter unit of claim 1, and configurable to concurrently transmit voice data and traffic data.

30. The transmitter unit of claim 29, wherein voice data for a particular voice call is allocated a portion of an available transmission resource for the duration of the voice call.

31. The transmitter unit of claim 29, wherein voice data for a particular voice call is assigned a particular sub-channel for the duration of the voice call.

32. The transmitter unit of claim 1, wherein pilot data is time division multiplexed with other data and is transmit periodically.

33. A communications system configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals, comprising:

a system data processor operative to receive and partition an input data stream into a plurality of channel data streams and to encode and modulate the plurality of channel data streams using orthogonal frequency division multiplexing (OFDM) modulation to generate one or more OFDM symbol streams, wherein each OFDM symbol stream comprises a sequence of OFDM symbols representative of data from one or more channel data streams, and wherein each OFDM symbols occupies one time slot and is selected and subsequently transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof;

at least one modulator coupled to the data processor, each modulator operative to receive and modulate a respective OFDM symbol stream to provide a modulated signal; and

at least one antenna coupled to the at least one modulator, each antenna operative to receive and transmit a respective modulated signal.

34. A receiver unit comprising:

at least one antenna, each antenna operative to receive at least one modulated signal;

at least one front end processor coupled to the at least one antenna, each front end processor operative to process a received signal from a respective antenna to generate samples;

at least one Fourier transform coupled to the at least one front end processor, each Fourier transform operative to receive samples from a respective front end processor and generate transformed representations of the samples;

a processor coupled to the at least one Fourier transform and operative to process the transformed representations to generate at least one symbol stream, each symbol stream corresponding to a particular transmission being processed; and

at least one demodulator coupled to the demultiplexer, each demodulator operative to receive and demodulate a respective symbol stream to generate demodulated data,

wherein the modulated signals are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof.

35. The receiver unit claim 34, further comprising:

at least one decoder coupled to the at least one demodulator, each decoder operative to receive and decode respective demodulated data to generate decoded data corresponding to the particular transmission being processed.

36. The receiver unit claim 34, wherein the receiver unit is operative to determine characteristics of at least one communications link used to receive the at least one modulated signal and to send information descriptive of the determined link characteristics.

37. The receiver unit claim 36, wherein the sent information comprises signal-to-noise-plus-interference ratio (C/I) values for the at least one communications link.

38. The receiver unit claim 36, wherein the sent information comprises a matrix corresponding to the at least one communications link.

39. A receiver unit comprising:

at least one antenna operative to receive at least one modulated signal that have been previously generated and transmitted by

partitioning an input data stream into a plurality of channel data streams,

encoding the plurality of channel data streams with at least one encoding scheme,

modulating the encoded data with at least one modulation scheme to generate modulation symbols,

selectively combining sets of modulation symbols into modulation symbol vectors, and

selectively combining modulation symbol vectors to form at least one modulation symbol vector stream,

wherein the modulation symbol vectors are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof; and

at least one processing unit coupled to the at least one antenna and operative to process at least one received signal to generate output data.

40. A method for generating and transmitting at least one modulated signal, comprising:

receiving an input data stream;

partitioning the input data stream into a plurality of channel data streams;

encoding the plurality of channel data streams with at least one encoding scheme;

modulating the encoded data with at least one modulation scheme to generate modulation symbols;

selectively combining sets of modulation symbols into modulation symbol vectors;

selectively combining modulation symbols to form at least one modulation symbol vector stream; and

transmitting the at least one modulation symbol vector stream from at least one antenna,

wherein the modulation symbol vectors are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof.

41. The method claim 40, further comprising:

demultiplexing each channel data stream into at least one sub-channel data stream, one sub-channel data stream for each of the at least one antenna used for transmission of the channel data stream.

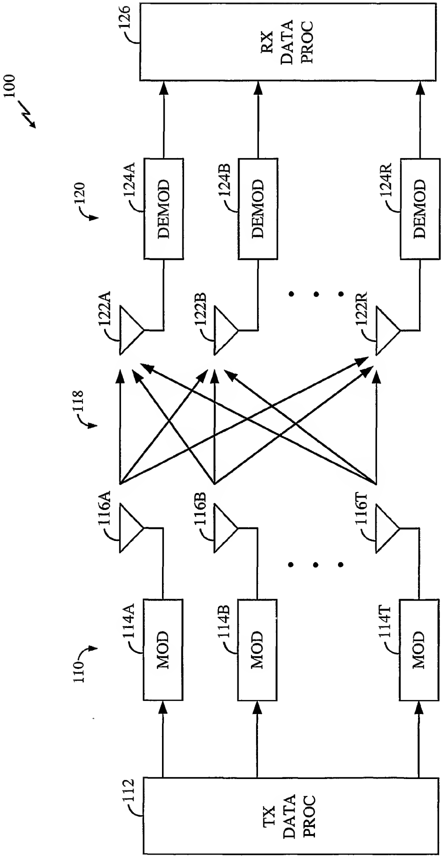
42. The method claim 41, further comprising:

demultiplexing each sub-channel data stream into at least one data sub-stream, one data sub-stream for each sub-band used for transmission of the channel data stream.

43. The method claim 42, wherein the modulating is performed using a particular modulation scheme for each channel data stream, or each sub-channel data stream, or each data sub-stream, or each combination thereof.

44. The method claim 40, further comprising:

pre-processing modulation symbols corresponding to a particular channel data stream in accordance with full or partial channel state information.



100
126
RX DATA PROC
120
124A
DEMOD
124B
DEMOD
124R
DEMOD
122A
122B
122R
118
116A
116B
116T
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114A
MOD
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MOD
112
TX DATA PROC

FIG. 1A

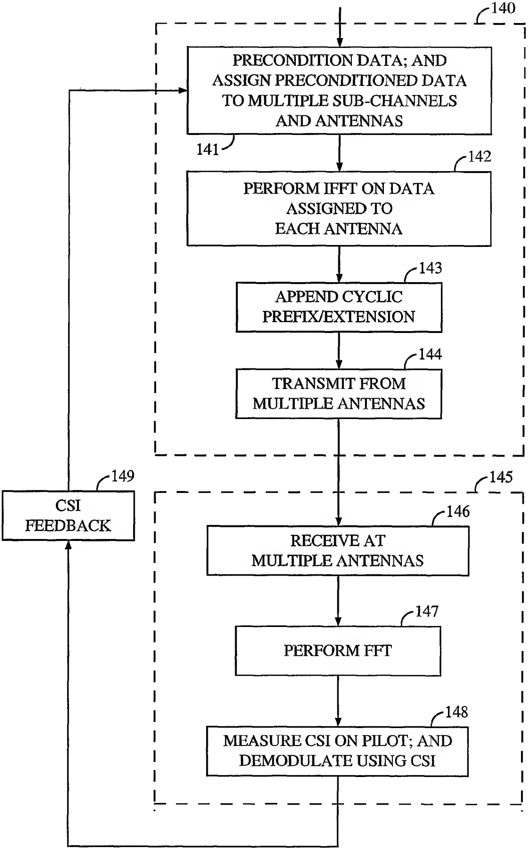

140
PRECONDITION DATA; AND ASSIGN PRECONDITIONED DATA TO MULTIPLE SUB-CHANNELS AND ANTENNAS
141
142
PERFORM IFFT ON DATA ASSIGNED TO EACH ANTENNA
143
APPEND CYCLIC PREFIX/EXTENSION
144
TRANSMIT FROM MULTIPLE ANTENNAS
149
CSI FEEDBACK
145
146
RECEIVE AT MULTIPLE ANTENNAS
147
PERFORM FFT
148
MEASURE CSI ON PILOT; AND DEMODULATE USING CSI

FIG. 1B

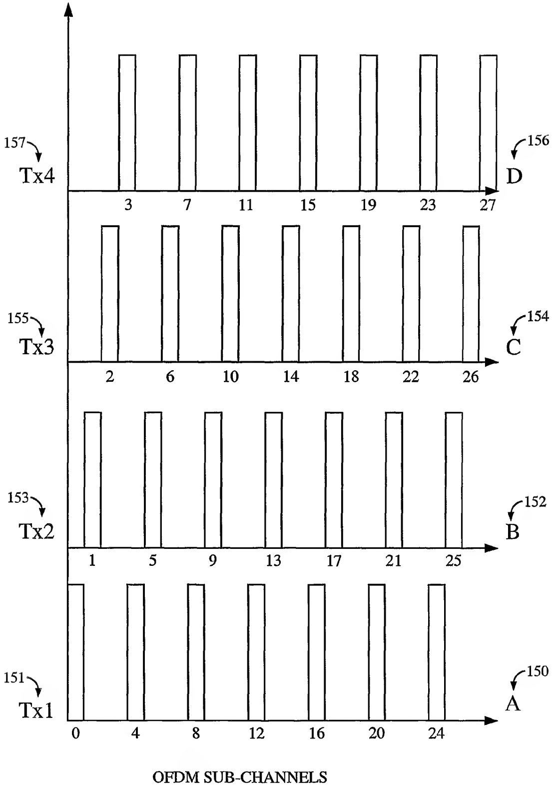

157
Tx4
156
D
3
7
11
15
19
23
27
155
Tx3
154
C
2
6
10
14
18
22
26
153
Tx2
152
B
1
5
9
13
17
21
25
151
Tx1
150
A
0
4
8
12
16
20
24
OFDM SUB-CHANNELS

FIG. 1C

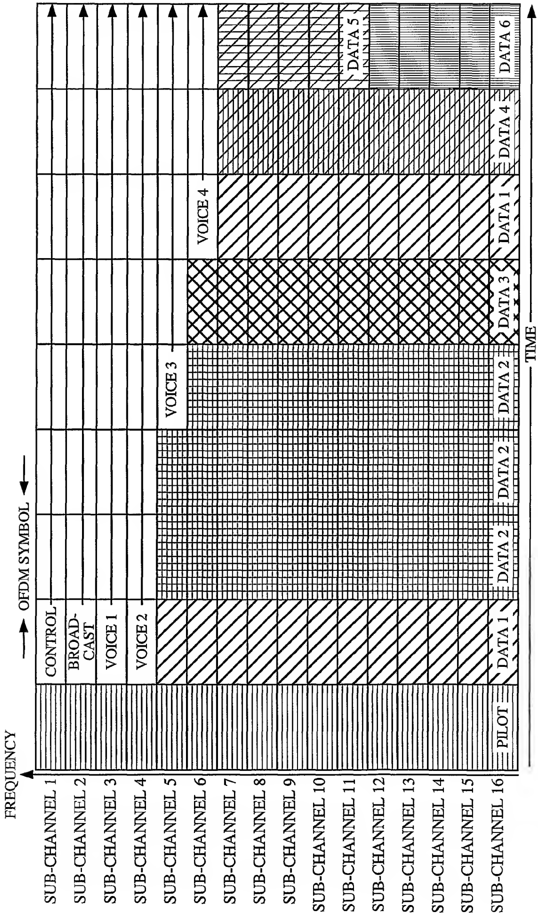

FREQUENCY
OFDM SYMBOL
TIME
SUB-CHANNEL 1
SUB-CHANNEL 2
SUB-CHANNEL 3
SUB-CHANNEL 4
SUB-CHANNEL 5
SUB-CHANNEL 6
SUB-CHANNEL 7
SUB-CHANNEL 8
SUB-CHANNEL 9
SUB-CHANNEL 10
SUB-CHANNEL 11
SUB-CHANNEL 12
SUB-CHANNEL 13
SUB-CHANNEL 14
SUB-CHANNEL 15
SUB-CHANNEL 16
PILOT
CONTROL
BROAD-CAST
VOICE 1
VOICE 2
VOICE 3
VOICE 4
DATA 1
DATA 2
DATA 2
DATA 2
DATA 3
DATA 1
DATA 4
DATA 5
DATA 6
TS1
TS2
TS3
TS4
TS5
TS6
TS7
TS8
TS9

FIG. 2

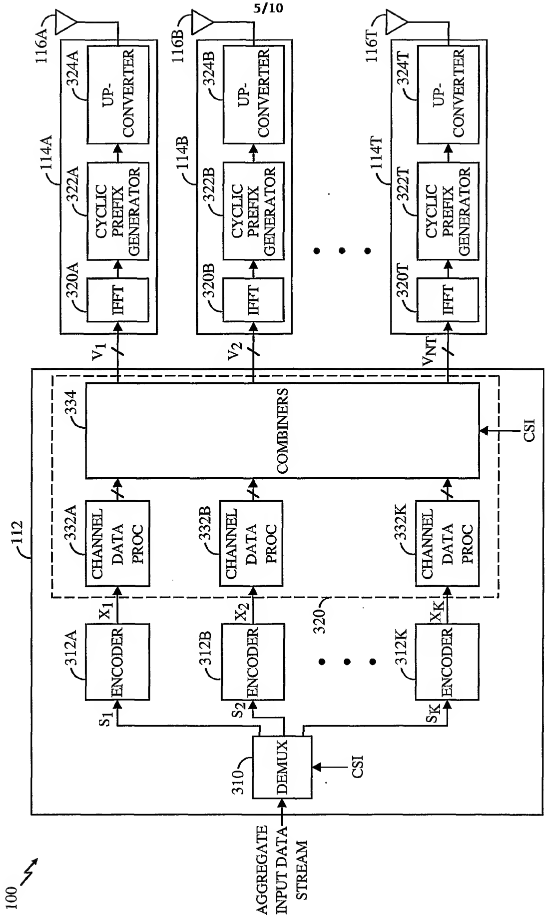
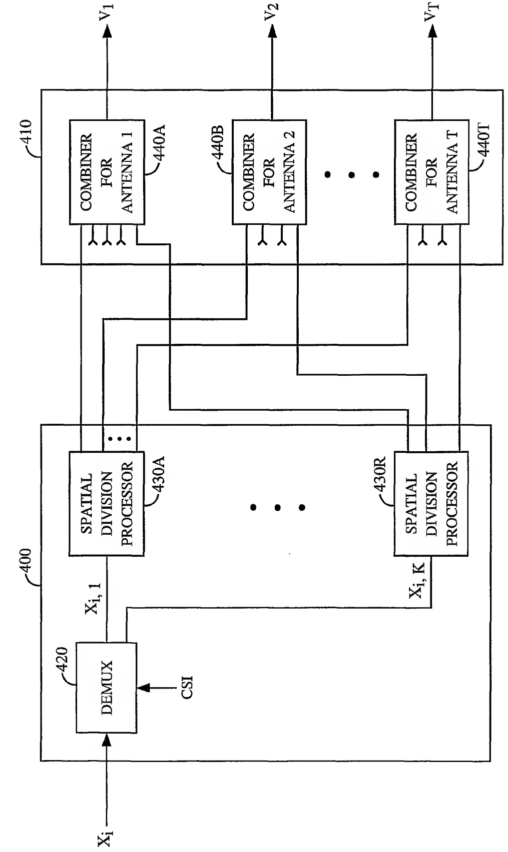

100
AGGREGATE INPUT DATA STREAM
112
310
DEMUX
CSI
S_1
S_2
S_K
312A
312B
312K
ENCODER
ENCODER
ENCODER
X_1
X_2
X_K
320
332A
332B
332K
CHANNEL DATA PROC
CHANNEL DATA PROC
CHANNEL DATA PROC
334
COMBINERS
CSI
V_1
V_2
V_{NT}
114A
114B
114T
320A
320B
320T
IFFT
IFFT
IFFT
322A
322B
322T
CYCLIC PREFIX GENERATOR
CYCLIC PREFIX GENERATOR
CYCLIC PREFIX GENERATOR
324A
324B
324T
UP-CONVERTER
UP-CONVERTER
UP-CONVERTER
116A
116B
116T

FIG. 3



X_i
DEMUX
420
CSI
400
$X_{i,1}$
$X_{i,K}$
SPATIAL DIVISION PROCESSOR
430A
SPATIAL DIVISION PROCESSOR
430R
410
COMBINER FOR ANTENNA 1
440A
COMBINER FOR ANTENNA 2
440B
COMBINER FOR ANTENNA T
440T
V_1
V_2
V_T

FIG. 4A

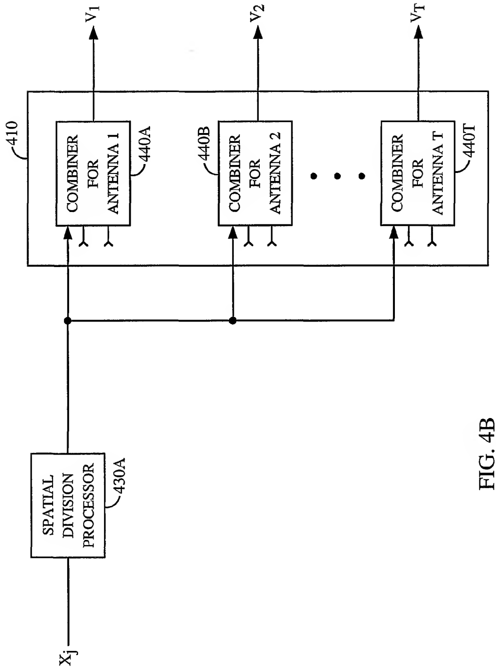

V_1
V_2
V_T
410
COMBINER FOR ANTENNA 1
440A
440B
COMBINER FOR ANTENNA 2
COMBINER FOR ANTENNA T
440T
SPATIAL DIVISION PROCESSOR
430A
X_j

FIG. 4B

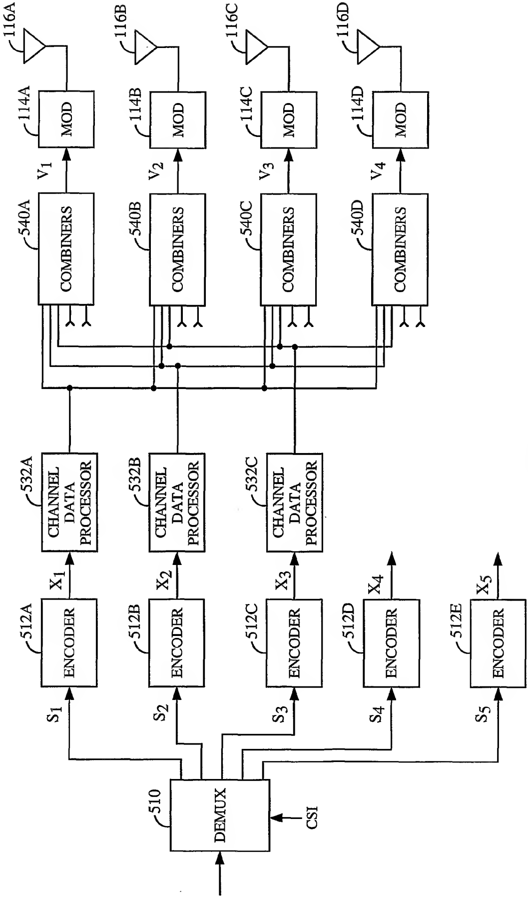

510
DEMUX
CSI
S1
S2
S3
S4
S5
512A
512B
512C
512D
512E
ENCODER
ENCODER
ENCODER
ENCODER
ENCODER
X1
X2
X3
X4
X5
532A
532B
532C
CHANNEL DATA PROCESSOR
CHANNEL DATA PROCESSOR
CHANNEL DATA PROCESSOR
540A
540B
540C
540D
COMBINERS
COMBINERS
COMBINERS
COMBINERS
V1
V2
V3
V4
114A
114B
114C
114D
MOD
MOD
MOD
MOD
116A
116B
116C
116D

FIG. 5A

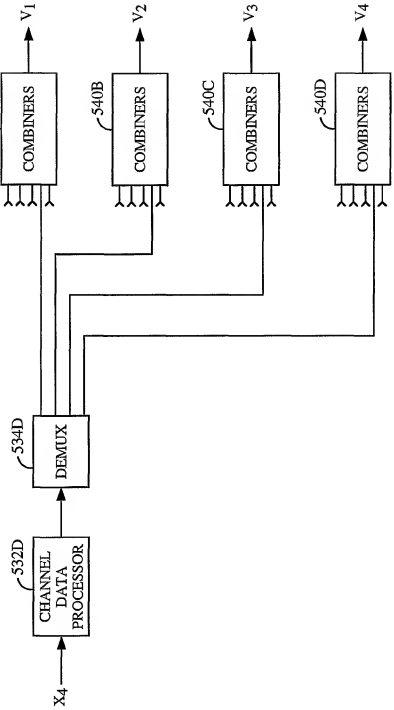

V_1
V_2
V_3
V_4
540A
540B
540C
540D
COMBINERS
COMBINERS
COMBINERS
COMBINERS
534D
DEMUX
532D
CHANNEL DATA PROCESSOR
X_4

FIG. 5B

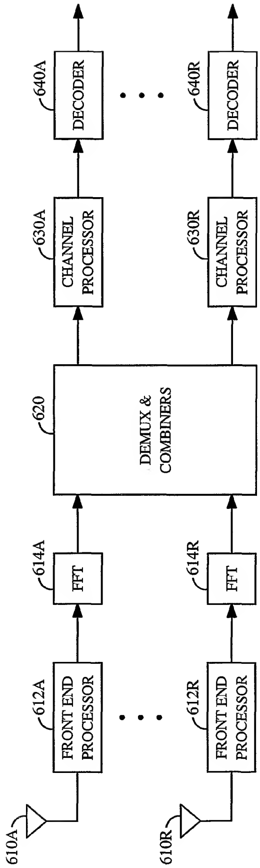

610A
610R
612A
FRONT END PROCESSOR
612R
FRONT END PROCESSOR
614A
FFT
614R
FFT
620
DEMUX & COMBINERS
630A
CHANNEL PROCESSOR
630R
CHANNEL PROCESSOR
640A
DECODER
640R
DECODER

FIG. 6

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(54) Title: METHOD AND APPARATUS FOR A RATE CONTROL IN A HIGH DATA RATE COMMUNICATION SYSTEM

(57) Abstract: A method and an apparatus for rate control in a high data rate (HDR) communication system are disclosed. An exemplary HDR communication system defines a set of data rates, at which an access point (AP) may send data packets to an access terminal (AT). The data rate is selected to maintain targeted packet error rate (PER). The AT's open loop algorithm measures received signal to interference and noise ratio (SINR) at regular intervals, and uses the information to predict an average SINR over the next packet duration. The AT's closed loop algorithm measures a packet error rate (PER) of the received signal, and uses the PER to calculate a closed loop correction factor. The loop correction factor is added to the SINR value predicted by the open loop, resulting in an adjusted SINR. The AT maintains a look up table, which comprises a set of SINR thresholds that represent a minimum SINR necessary to successfully decode a packet at each data rate. The AT uses the adjusted set of SINR thresholds in the look up table to select the highest data rate, the SINR threshold of which is below the predicted SINR. The AT then requests, over the reverse link, that the AP send the next packet at this data-rate.

METHOD AND APPARATUS FOR A RATE CONTROL IN A HIGH DATA RATE COMMUNICATION SYSTEM

BACKGROUND OF THE INVENTION

I. Field of the Invention

The current invention relates to communication. More particularly, the present invention relates to a novel method and apparatus for adaptive rate selection in a wireless communication system.

II. Description of the Related Art

A modern communications system is required to support a variety of applications. One such communications system is a code division multiple access (CDMA) system that conforms to the "TIA/EIA/IS-95 Mobile Station-Base Station Compatibility Standard for Dual-Mode Wide-Band Spread Spectrum Cellular System," hereinafter referred to as the IS-95 standard. The CDMA system supports voice and data communication between users over a terrestrial link. The use of CDMA techniques in a multiple access communication system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM," both assigned to the assignee of the present invention and incorporated herein by reference.

In a CDMA system, communications between users are conducted through one or more base stations. In wireless communication systems, forward link refers to the channel through which signals travel from a base station to a subscriber station, and reverse link refers to channel through which signals travel from a subscriber station to a base station. By transmitting data on a reverse link to a base station, a first user on one subscriber station may communicate with a second user on a second subscriber station. The base

station receives the data from the first subscriber station and routes the data to a base station serving the second subscriber station. Depending on the location of the subscriber stations, both may be served by a single base station or multiple base stations. In any case, the base station serving the second subscriber station sends the data on the forward link. Instead of communicating with a second subscriber station, a subscriber station may also communicate with a wireline telephone through a public switched telephone network (PSTN) coupled to the base station, or a terrestrial Internet through a connection with a serving base station.

Given the growing demand for wireless data applications, the need for very efficient wireless data communication systems has become increasingly significant. The IS-95 standard specifies transmitting traffic data and voice data over the forward and reverse links. A method for transmitting traffic data in code channel frames of fixed size is described in detail in U.S. Patent No. 5,504,773, entitled "METHOD AND APPARATUS FOR THE FORMATTING OF DATA FOR TRANSMISSION", assigned to the assignee of the present invention and incorporated by reference herein. In accordance with the IS-95 standard, the traffic data or voice data is partitioned into code channel frames that are 20 milliseconds wide with data rates as high as 14.4 Kbps.

In mobile radio communication systems, there are significant differences between the requirements for providing voice and data services (i.e., non-voice services such as Internet or fax transmissions). Unlike data services, voice services require stringent and fixed delays between speech frames. Typically, the overall one-way delay of speech frames used for transmitting voice information must be less than 100 msec. By contrast, transmission delays that occur during data (i.e., non-voice information) services can vary and larger delays then those that can be tolerated for voice services can be utilized.

Another significant difference between voice and data services is that, in contrast to data services, voice services require a fixed and common grade of service. Typically, for digital systems providing voice services, this requirement is met by using a fixed and equal transmission rate for all users

and a maximum tolerable error rate for speech frames. For data services, the grade of service can vary from user to user.

Yet another difference between voice services and data services is that voice services require a reliable communication link which, in the case of a CDMA communication system, is provided using a soft handoff. A soft handoff requires the redundant transmission of the same voice information from two or more base stations to improve reliability. A soft handoff method is disclosed in U.S. Patent No. 5,101,501, entitled "SOFT HANDOFF IN A CDMA CELLULAR TELEPHONE SYSTEM." This additional reliability is not required to support data services, because data packets received in error can be retransmitted.

As a mobile station moves in a mobile radio communication system, the quality of the forward link (and the capacity of the forward link to transmit data) will vary. Thus, at some moments a given forward link between a base station and a mobile station will be able to support a very high data transmission and, at other moments, the same forward link may only be able to support a much reduced data transmission rate. In order to maximize the throughput of information on the forward link, it would be desirable if the transmission of data on the forward link could be varied so as to increase the data rate during those intervals where the forward link can support a higher transmission rate.

When non-voice traffic is being sent from a base station to a mobile station on a forward link, it may be necessary to send control information from the mobile station to the base station. At times, however, even though the forward link signal may be strong, the reverse link signal may be weak, thereby resulting in a situation where the base station cannot receive control information from the mobile station. In such situations, where the forward link and the reverse link are unbalanced, it may be undesirable to increase the transmit power on the reverse link in order to improve the reception quality of the control information at the base station. For example, in CDMA systems, increasing the transmit power on the reverse link would be undesirable, as such

a power increase could adversely affect the reverse link capacity seen by other mobile stations in the system. It would be desirable to have a data transmission system where the forward and reverse links associated with each mobile station were maintained in a balanced state without adversely impacting the reverse link capacity. It would be further desirable if such a system could maximize the throughput of non-voice data on individual forward links when such links are sufficiently strong to support higher data rates.

One approach to the aforementioned requirements in high data rate (HDR) systems is to keep the transmit power fixed and vary the data rate depending on the users' channel conditions. Consequently, in a modern HDR system, Access Point(s) (APs) always transmit at maximum power to only one Access Terminal (AT) in each time slot, and the AP uses rate control to adjust the maximum rate that the AT can reliably receive. An AP is a terminal allowing high data rate transmission to ATs.

As used in this document, a time slot is a time interval of finite length, e.g., 1.66 ms. A time slot can contain one or more packets. A packet is a structure, comprising a preamble, a payload, and a quality metric, e.g., a cyclical redundancy check (CRC). The preamble is used by an AT to determine whether a packet has been intended for the AT.

An exemplary HDR system defines a set of data rates, ranging from 38.4kbps to 2.4 Mbps, at which an AP may send data packets to an AT. The data rate is selected to maintain a targeted packet error rate (PER). The AT measures the received signal to interference and noise ratio (SINR) at regular intervals, and uses the information to predict an average SINR over the next packet duration. An exemplary prediction method is disclosed in co-pending application serial number 09/394,980 entitled "SYSTEM AND METHOD FOR ACCURATELY PREDICTING SIGNAL TO INTERFERENCE AND NOISE RATIO TO IMPROVE COMMUNICATIONS SYSTEM PERFORMANCE," assigned to the assignee of the present invention and incorporated herein by reference.

FIG. 1 shows a conventional open loop rate control apparatus **100**. A stream of past SINR values at instances [n-m], . . .[n-1], [n], each measured over a duration of a corresponding packet, is provided to a predictor **102**. The predictor **102** predicts the average SINR over the next packet duration in accordance with the following equation:

$$OL\_SINR_{Predicted} = OL\_SINR_{Estimated} - K \cdot \sigma_e \qquad (1)$$

In Equation (1), $OL\_SINR_{Predicted}$ is a SINR predicted by the open loop for the next packet, $OL\_SINR_{Estimated}$ is a SINR estimated by the open loop based on past SINR values, K is a back-off factor, and σ_e is a standard deviation of an error metric.

The estimated SINR may be obtained, for example, by selecting an output from a bank of low pass filters acting on past measurements of SINR. Selection of a particular filter from the filter bank may be based on an error metric, defined as a difference between the particular filter output and measured SINR over a packet duration immediately following the output. The predicted SINR is obtained by backing off from the filter output by an amount equal to the product of the back-off factor K and the standard deviation σ_e of the error metric. The value of the back-off factor K is determined by a back-off control loop, which ensures that a tail probability, i.e., probability that predicted SINR exceeds the measured SINR, is achieved for a certain percentage of time.

The $SINR_{Predicted}$ value is provided to a look up table **104** that maintains a set of SINR thresholds that represent the minimum SINR required to successfully decode a packet at each data rate. An AT (not shown) uses the look up table **104** to select the highest data rate whose SINR threshold is below the predicted SINR, and requests that an AP (not shown) send the next packet at this datarate.

The aforementioned method is an example of an open loop rate control method that determines the best rate at which to receive the next packet, based

only on the measurement of the channel SINR, without any information about the decoder error rate (for packets of each data rate) at a given SINR under the prevailing channel conditions. Any open loop rate control algorithm suffers from several shortcomings, some of which are discussed below. First, a certain tail probability, e.g., 2%, does not imply a PER of 2%. This is because PER is a monotonically decreasing function of SINR, with a finite slope that depends on the coding scheme and channel conditions. However, Equation (1) assumes "brick wall" PER characteristics, i.e., a packet is guaranteed to be decoded whenever the SINR exceeds the threshold for the corresponding rate, and a packet is in error whenever the SINR falls below the threshold. Furthermore, the open loop rate control method uses a fixed set of SINR thresholds, which ensures packet error rates close to the target error rate under worst-case channel conditions. However, the performance of the decoder depends not only on the SINR, but also on channel conditions. In other words, a method that uses a fixed set of SINR thresholds for all channels achieves different packet error rates on different channels. Consequently, while the open loop method works optimally under the worst-case channel conditions, it is possible that under typical channel conditions, the method results in much lower error rates than is necessary, at the expense of diminished throughput. Additionally, a practical rate control method necessitates a small, finite set of data rates. The rate selection method always selects the nearest lower data rate in order to guarantee an acceptable PER. Thus, rate quantization results in loss of system throughput.

Therefore, there exists a need to address deficiencies of the existing method.

SUMMARY OF THE INVENTION

The present invention is directed to a novel method and apparatus for adaptive rate selection in a wireless communication system. Accordingly, in one aspect of the invention, SINR predicted by an open loop method is modified by a closed loop correction. The closed loop correction is updated in accordance with packet error events and a target error rate.

In another aspect of the invention, the closed loop correction is advantageously updated in accordance with a frequency with which packets are received.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, objects, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1 illustrates a block diagram of a conventional, open loop rate-control apparatus.

FIG. 2 illustrates a block diagram of an apparatus for a rate control method in accordance with one embodiment of the invention.

FIG. 3 illustrates a flowchart of an exemplary method of updating an outer loop correction.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 2 illustrates an exemplary communication system **200** capable of implementing embodiments of the invention. An AP **204** transmits signals to an AT **202** over a forward link **206a**, and receives signals from the AT **202** over a reverse link **206b**. The communication system **200** can be operated bi-directionally, each of the terminals **202, 204** operating as a transmitter unit or a receiver unit, or both concurrently, depending on whether data is being transmitted from, or received at, the respective terminal **202, 204**. In a cellular wireless communication system embodiment, the transmitting terminal **204** can be a base station (BS), the receiving terminal **202** can be a mobile station (MS), and the forward link **206a** and reverse link **206b** can be electromagnetic spectra.

The AT **202** contains an apparatus for a rate control method in accordance with one embodiment of the present invention. The apparatus contains two control loops, an open loop and a closed loop.

The open loop, comprising a SINR predictor **208** and a look up table **210**, controls the forward-link data rate based on the difference between the average SINR of the next packet and SINR thresholds of all the data rates. A signal arriving at the AT **202** from the AP **204** over the forward link **206a** in packets is provided to a decoder **212**. The decoder **212** measures an average SINR over the duration of each packet, and provides the SINRs to the SINR predictor **208**.

In one embodiment, the predictor **208** predicts a SINR ($OL\_SNIR_{\Pr edicted}$) value of the next packet in accordance with Equation (1). However, one skilled in the art will understand that any open loop method, not limited to the one expressed by Equation (1), may be used. The $OL\_SNIR_{\Pr edicted}$ value is provided to the look up table **210**. The look up table **210** maintains a set of SINR thresholds that represents the minimum SINR required to successfully decode a packet at each data rate. The set of SINR thresholds is adjusted by the operation of the closed loop.

The closed loop utilizes PER information provided by the decoder **212** to determine a closed loop correction value ***L*** in block **214**. The closed loop correction value ***L*** adjusts the set of SINR thresholds in the look up table **204** in accordance with the following equation:

$$CL\_SINR_{\Pr edicted} = OL\_SINR_{\Pr edicted} + L, \tag{2}$$

In equation (2), ***L*** represents the closed loop correction to the open loop prediction of SINR over the next packet duration. Adding ***L*** to the SINR predicted by the open loop algorithm in Equation (1) is equivalent to subtracting ***L*** from the SINR thresholds used for rate control. Because the correction term ***L*** is updated in accordance with PER information, which reflects the prevailing channel conditions, the set of SINR thresholds is better matched to the prevailing channel conditions.

The AT **202** uses the adjusted set of SINR thresholds in the look up table **210** to select the highest data rate, the SINR threshold of which is below the predicted SINR. The AT **202** then requests, over the reverse link **206b**, that the AP **204** sends the next packet at this data-rate.

Although the predictor **208**, the decoder **212**, and the closed loop correction block **214** are shown as separate elements, one skilled in the art will appreciate that the physical distinction is made for explanatory purposes only. The predictor **208**, the decoder **212**, and the closed loop correction block **214** may be incorporated into a single processor accomplishing the above-mentioned processing. Thus, the processor may be, e.g., a general-purpose processor, a digital signal processor, a programmable logic array, and the like. Furthermore, the look up table **210** is a space in a memory. The memory may be a part of the above-mentioned processor or processors, or be a separate element. The implementation of the memory is a design choice. Thus, the memory can be any media capable of storing information, e.g., a magnetic disk, a semiconductor integrated circuit, and the like.

FIG. 3 illustrates a flowchart of an exemplary method of updating L to ensure the best possible throughput with acceptable error rates.

In step **300**, a normalized activity factor (AF) variable is initialized by an AT (not shown) to a value of zero or one. The AF quantifies a time fraction for which the AT receives packets on the forward link. An AF being equal to one implies that the AT **202** is receiving packets most of the time, whereas an AF being equal to zero implies that the forward link to the given AT is mostly idle. In one embodiment, the AF is initialized at the instant when the AT initiates a new communication. In that case, it may be advantageous to initialize the AF to one because the AT is receiving packets. The AF is updated at the end of each time slot according to the following equations:

$$AF_{New} = (1-f)\cdot AF_{Old} + f, \tag{3}$$

or

$$AF_{New} = (1-f)\cdot AF_{Old}, \tag{4}$$

where:

$f \in (0,1)$ is a parameter controlling a rate of change of the AF. In one embodiment of the invention, f is set to 1/50.

Equation (3) is used when the AT finds a packet preamble at the beginning of a time slot, or is still demodulating a packet whose preamble was detected in an earlier time slot. This happens when the AT sends a request for data, and an AP (not shown) sends the requested data. Equation (4) is used when the AT is not in the middle of packet demodulation, searches for a packet preamble, and fails to find the preamble. This happens when the AT sends a request for data, and the AP fails to receive or ignores the request for data, and decides to serve some other AT in the system.

In step **300**, the outer loop correction variable L is also initialized by the AT. L can be initialized to any value between L_{min} and L_{max}. L_{min}, L_{max} may attain any value. Exemplary values are cited below. In one embodiment, L is initialized to 0 dB.

In step **300**, a mode of operation is also initialized. There are two modes: a normal mode and a fast attack mode. The motivation behind defining the two modes for the rate control algorithm is based on the knowledge that an optimal step size for upward and downward corrections of L depends on a target PER, the packet arrival process, and preamble false alarm statistics. While the

preamble false alarm statistics are relatively constant and correlated with the outer loop term L, the packet arrival process is time varying and unknown *apriori* at the AT. As discussed above, data traffic tends to be bursty, with an idle state characterized by infrequent packet arrival, and busy, with frequent packet arrival. Consequently, the normal mode is used during steady state. Fast attack mode designed to recover quickly from long periods of inactivity is used when preamble false alarms tend to drive the rate control algorithm toward the conservative regime.

The rules for determining the mode of the algorithm, as well as the rules for updating L, are based on the detection of good or bad packets. The access terminal is said to receive a good packet if it detects the packet preamble, demodulates and decodes the packet, and recovers a valid CRC. The access terminal is said to receive a bad packet if it detects a packet preamble, but upon demodulating and decoding the packet, it obtains an invalid CRC.

The transition to the fast attack mode occurs if all the following conditions are satisfied:

$$L < L_{AMThreshold}, \tag{5}$$

$$AF < AF_{Idle}, \text{ and} \tag{6}$$

the two most recently received packets are good.

In Equations (5)-(6), $L_{AMThreshold}$ is a threshold controlling the transition to the fast attack mode with respect to L. In one embodiment of the invention, the $L_{AMThreshold}$ threshold is set to 0dB. AF_{Idle} is a threshold controlling the transition to the fast attack mode with respect to AF. In one embodiment of the invention, the AF_{Idle} threshold is set to 10%.

The transition to the normal mode occurs if any of the following conditions are satisfied:

$$L \geq L_{NMThreshold}, \tag{7}$$

$$AF \geq AF_{Busy}, \text{ or} \tag{8}$$

the most recently received packet is bad.

In Equations (7)-(8), $L_{NMThreshold}$ is a threshold controlling the transition to the normal mode with respect to L. In one embodiment of the invention, the $L_{NMThreshold}$ threshold is set to 2dB. AF_{Busy} is a threshold controlling the transition to the normal mode with respect to A. In one embodiment of the invention, the AF_{Busy} threshold is set to 25%.

Upon finishing initialization, the AT waits for a new time slot. Once a time slot is detected in step **302**, the AF is updated in step **304** using Equations (3) or (4), and the mode is updated in step **306** using Equations (5)-(6) or (7)-(8).

In step **308**, a test is made whether the slot belonged to a new packet. If a new packet has not been detected, the method returns to step **302**. If a new packet has been detected, the packet is tested in step **310**, and if a bad packet has been detected, the method continues in step **312**. In step **312**, the value of L is updated in accordance with the following equation:

$$L_{new} = \max(L_{old} - \delta, L_{\min}), \qquad (9)$$

where δ is a step size. In one embodiment of the invention, the step size is set to 0.25 dB. L_{min} is the minimum value that L can attain. In one embodiment of the invention, the value of L_{min} is limited to -1 dB. The method then returns to step **302**.

If, in step **310**, a good packet was detected, the method continues in step **314**. In step **314**, the mode is tested. If the AT is in fast attack mode, the value of L is updated in accordance with the following equation in step **316**:

$$L_{new} = \min(L_{Old} + \delta', L_{\max}), \qquad (9)$$

where:

δ' is a step size. In one embodiment of the invention, the step size is set to 0.25 dB. L_{max} is the maximum value that L can attain. In one embodiment of the invention, the value of L_{max} is limited to 3 dB. Once L is updated in step **318** the method returns to step **302**.

If a normal mode was detected in step **314**, the method continues in step **318**, where the value of L is updated in accordance with the following equation:

$$L_{new} = \min(L_{old} + TARGET\_PER \cdot \delta, L_{\max}). \qquad (10)$$

In Equation (9), δ is a step size. In one embodiment of the invention, the step size is set to 0.25 dB. *TARGET_PER* is the PER to be maintained. L_{max} is the maximum value that L can attain. In one embodiment of the invention, the value of L_{max} is limited to 3 dB. Once L is updated in step **318** the method returns to step **302**.

The previous description of the preferred embodiments is provided to enable any person skilled in the art to make or use the present invention. The

various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without the use of the inventive faculty. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

CLAIMS

1. A method for rate selection in a wireless communication system comprising the steps of:

determining an open loop prediction of signal to noise and interference ratio;

determining a closed loop correction; and

selecting a data rate in accordance with said open loop prediction and said closed loop correction.

2. The method of claim 1 wherein said step of determining a closed loop correction comprises the steps of:

determining a quality of a received packet; and

decreasing said closed loop correction if said quality is bad.

3. The method of claim 2 wherein said step of decreasing is carried out in accordance with an equation:

$$L_{new} = \max(L_{old} - \delta, L_{\min}),$$

wherein L_{new} is an updated value of said outer loop correction, L_{old} is a previous value of said outer loop correction, δ is a step size, and L_{min} is the minimum value that said outer loop correction can attain.

4. The method of claim 1 wherein said step of determining a closed loop correction comprises the steps of:

determining a quality of a received packet; and

increasing said closed loop correction if said quality is good.

5. The method of claim 4 wherein said step of increasing comprises the steps of:

determining a mode of operation; and

increasing said closed loop correction in accordance with said mode of operation.

6. The method of claim 5 wherein said step of determining a mode of operation comprises the steps of:

determining a time fraction for which a packet is received; and

selecting said mode of operation in accordance with said time fraction.

7. The method of claim 6 wherein when a packet is detected said step of determining is carried out in accordance with an equation:

$$AF_{New} = (1 - f) \cdot AF_{Old} + f$$

wherein AF_{new} is an updated value of said time fraction, L_{old} is a previous value of said time fraction, and $f \in (0,1)$ is a parameter controlling a rate of change of said time fraction.

8. The method of claim 6 wherein when a packet detection fails said step of determining is carried out in accordance with an equation:

$$AF_{New} = (1 - f) \cdot AF_{Old},$$

wherein AF_{new} is an updated value of said time fraction, L_{old} is a previous value of said time fraction, and $f \in (0,1)$ is a parameter controlling a rate of change of said time fraction.

9. The method of claim 6 wherein the step of selecting comprises the step of selecting a fast attack mode if all of the following conditions are satisfied:

$L < L_{AMThreshold}$,
$AF < AF_{Idle}$,
the two most recently received packets are good,

wherein $L_{AMThreshold}$ is a threshold controlling the transition to said fast attack mode with respect to L and AF_{Idle} is a threshold controlling the transition to said fast attack mode with respect to AF.

10. The method of claim 6 wherein the step of selecting comprises the step of selecting a normal mode if any of the following conditions are satisfied:

$L \geq L_{NMThreshold}$,
$AF \geq AF_{Busy}$, or
the most recently received packet is bad,

wherein $L_{NMhreshold}$ is a threshold controlling the transition to said normal mode with respect to *L*. AF_{Idle} is a threshold controlling the transition to said normal mode with respect to *AF*; and

11. The method of claim 5 wherein when in a fast attack mode of operation said step of increasing is carried out in accordance with an equation:

$$L_{new} = \min(L_{old} + \delta', L_{\max}),$$

wherein L_{new} is an updated value of said outer loop correction, L_{old} is a previous value of said outer loop correction, δ' is a step size, and L_{max} is the maximum value that said outer loop correction can attain.

12. The method of claim 5 wherein when in a normal mode of operation said step of increasing is carried out in accordance with an equation:

$$L_{new} = \min(L_{old} + TARGET\_PER \cdot \delta, L_{\max}),$$

wherein L_{new} is an updated value of said outer loop correction, L_{old} is a previous value of said outer loop correction, *TARGET_PER* is a packet error rate to be attained, δ' is a step size, and L_{max} is the maximum value that said outer loop correction can attain.

13. The method of claim 1 wherein said step of selecting comprises the steps of:

summing said open loop prediction of signal to noise and interference ratio and said closed loop correction; and

determining said data rate as the highest data rate, a signal to noise ratio of which is below said summed signal to noise ratio.

14. An apparatus for selecting rate in a wireless communication system, comprising:

a processor; and

a storage medium coupled to the processor and containing a set of instructions executable by the processor to:

determine an open loop prediction of signal to noise and interference ratio;

determine a closed loop correction; and

select a data rate in accordance with said open loop prediction and said closed loop correction.

15. The apparatus of claim 14 wherein said processor comprises a signal to noise and interference ratio predictor and a closed loop correction calculator.

16. The apparatus of claim 14 wherein said processor is configured to decrease said closed loop correction if a quality of a received packet is bad.

17. The apparatus of claim 16 wherein said processor is configured to decrease said closed loop correction in accordance with an equation:

$$L_{new} = \max(L_{old} - \delta, L_{\min}),$$

wherein L_{new} is an updated value of said outer loop correction, L_{old} is a previous value of said outer loop correction, δ is a step size, and L_{min} is the minimum value that said outer loop correction can attain.

18. The apparatus of claim 14 wherein said processor is configured to increase said closed loop correction if a quality of a received packet is good.

19. The apparatus of claim 18 wherein said processor is configured to:

determine a mode of operation; and

increase said closed loop correction in accordance with said mode of operation.

20. The apparatus of claim 19 wherein said processor is configured to:

determine a time fraction for which a packet is received; and

select said mode of operation in accordance with said time fraction.

21. The apparatus of claim 20 wherein when a packet is detected said processor is configured to determine said time fraction in accordance with an equation:

$$AF_{New} = (1 - f) \cdot AF_{Old} + f$$

wherein AF_{new} is an updated value of said time fraction, L_{old} is a previous value of said time fraction, and $f \in (0,1)$ is a parameter controlling a rate of change of said time fraction.

22. The apparatus of claim 20 wherein when a packet detection fails said processor is configured to determine said time fraction in accordance with an equation:

$$AF_{New} = (1 - f) \cdot AF_{Old},$$

wherein AF_{new} is an updated value of said time fraction, L_{old} is a previous value of said time fraction, and $f \in (0,1)$ is a parameter controlling a rate of change of said time fraction.

23. The apparatus of claim 20 wherein said processor is configured to select a fast attack mode if all of the following conditions are satisfied:

$L < L_{AMThreshold}$,
$AF < AF_{Idle}$,
the two most recently received packets are good,

wherein $L_{AMThreshold}$ is a threshold controlling the transition to said fast attack mode with respect to L and AF_{Idle} is a threshold controlling the transition to said fast attack mode with respect to AF.

24. The apparatus of claim 20 wherein said processor is configured to select a normal mode if any of said conditions are satisfied:

$L \geq L_{NMThreshold}$,
$AF \geq AF_{Busy}$, or
the most recently received packet is bad,

wherein $L_{NMhreshold}$ is a threshold controlling the transition to said normal mode with respect to L and AF_{Idle} is a threshold controlling the transition to said normal mode with respect to AF.

25. The apparatus of claim 19 wherein when in a fast attack mode of operation said processor is configured to increase said closed loop correction in accordance with an equation:

$$L_{new} = \min(L_{old} + \delta', L_{\max}),$$

wherein L_{new} is an updated value of said outer loop correction, L_{old} is a previous value of said outer loop correction, δ' is a step size, and L_{max} is the maximum value that said outer loop correction can attain.

26. The apparatus of claim 19 wherein when in a normal mode of operation said processor is configured to increase said closed loop correction in accordance with an equation:

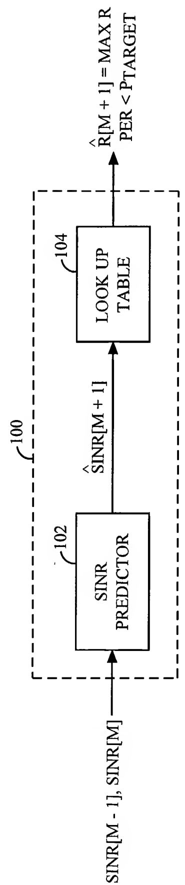
$$L_{new} = \min(L_{old} + TARGET\_PER \cdot \delta, L_{\max}),$$

wherein L_{new} is an updated value of said outer loop correction, L_{old} is a previous value of said outer loop correction, *TARGET_PER* is a packet error rate to be attained, δ' is a step size, and L_{max} is the maximum value that said outer loop correction can attain.

27. The apparatus of claim 14 wherein the processor is configured to:

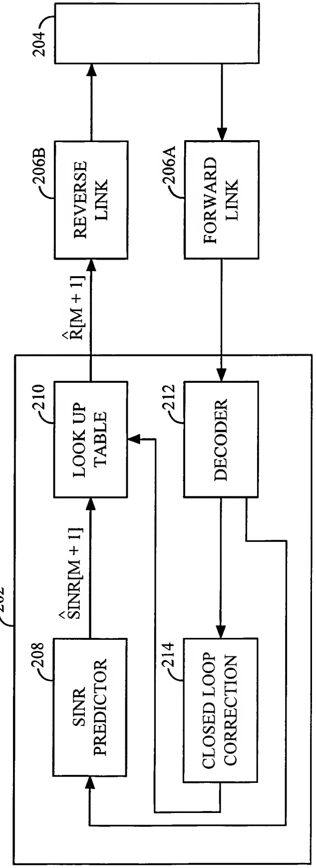
sum said open loop prediction of signal to noise and interference ratio and said closed loop correction; and

determine said data rate as the highest data rate, a signal to noise ratio of which is below said modified signal to noise ratio.



$\hat{R}[M+1]$ = MAX R
PER < PTARGET
100
104
LOOK UP TABLE
$\hat{SINR}[M+1]$
102
SINR PREDICTOR
SINR[M - 1], SINR[M]

FIG. 1



204
206B
REVERSE LINK
206A
FORWARD LINK
$\hat{R}[M+1]$
210
LOOK UP TABLE
212
DECODER
$\hat{SINR}[M+1]$
202
208
SINR PREDICTOR
214
CLOSED LOOP CORRECTION

FIG. 2

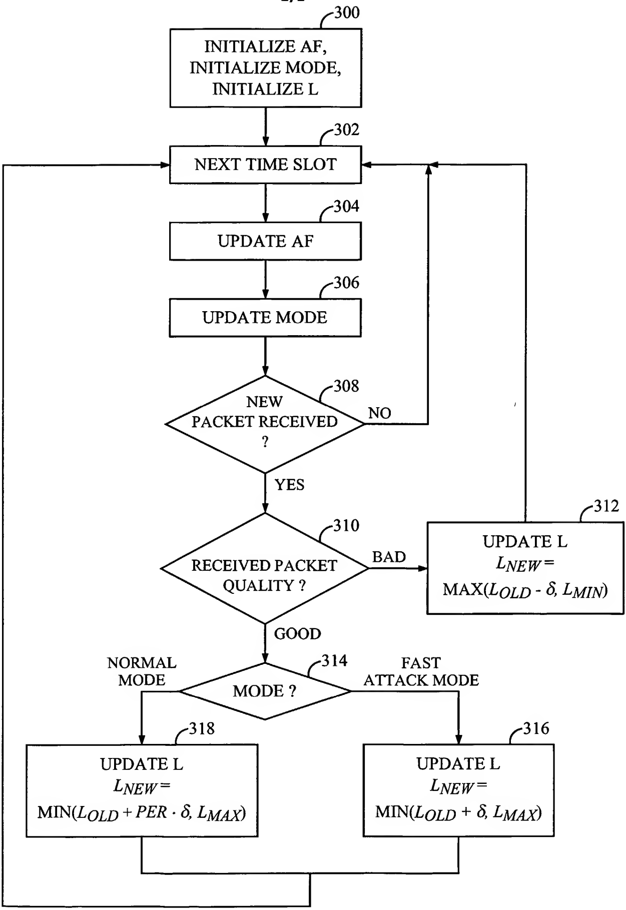

300
INITIALIZE AF, INITIALIZE MODE, INITIALIZE L
302
NEXT TIME SLOT
304
UPDATE AF
306
UPDATE MODE
308
NEW PACKET RECEIVED ?
NO
YES
310
RECEIVED PACKET QUALITY ?
BAD
312
UPDATE L
$L_{NEW} = MAX(L_{OLD} - \delta, L_{MIN})$
GOOD
314
MODE ?
NORMAL MODE
FAST ATTACK MODE
318
UPDATE L
$L_{NEW} = MIN(L_{OLD} + PER \cdot \delta, L_{MAX})$
316
UPDATE L
$L_{NEW} = MIN(L_{OLD} + \delta, L_{MAX})$

FIG. 3

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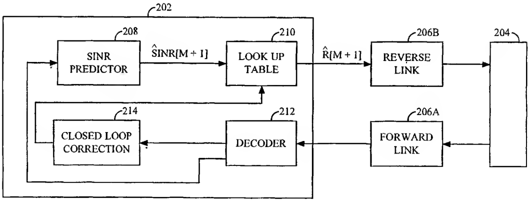
(54) Title: METHOD AND APPARATUS FOR A RATE CONTROL IN A HIGH DATA RATE COMMUNICATION SYSTEM



(57) Abstract: A method and an apparatus for rate control in a high data rate (HDR) communication system are disclosed. An exemplary HDR communication system defines a set of data rates, at which an access point (AP) may send data packets to an access terminal (AT). The data rate is selected to maintain targeted packet error rate (PER). The AT's open loop algorithm measures received signal to interference and noise ratio (SINR) at regular intervals, and uses the information to predict an average SINR over the next packet duration. The AT's closed loop algorithm measures a packet error rate (PER) of the received signal, and uses the PER to calculate a closed loop correction factor. The loop correction factor is added to the SINR value predicted by the open loop, resulting in an adjusted SINR. The AT maintains a look up table, which comprises a set of SINR thresholds that represent a minimum SINR necessary to successfully decode a packet at each data rate. The AT uses the adjusted set of SINR thresholds in the look up table to select the highest data rate, the SINR threshold of which is below the predicted SINR. The AT then requests, over the reverse link, that the AP send the next packet at this data-rate.

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INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER
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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 899 906 A (LUCENT TECHNOLOGIES INC) 3 March 1999 (1999-03-03) abstract paragraphs '0002!-'0007!,'0014!-'0038!,'0040!,'0041! figures 10-12 ---	1-27
A	US 5 541 955 A (JACOBSMEYER JAY M) 30 July 1996 (1996-07-30) abstract; figures 3,4,23 column 6, line 28 - line 49 column 11, line 45 -column 23, line 29 column 29, line 5 -column 30, line 2 column 34, line 9 -column 38, line 51 -----	1-27

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
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Name and mailing address of the ISA	Authorized officer
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3

INTERNATIONAL SEARCH REPORT

Information on patent family members

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Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 0899906	A	03-03-1999	US	6108374	A	22-08-2000
			CA	2244428	A1	24-02-1999
			EP	0899906	A2	03-03-1999
			JP	11150571	A	02-06-1999
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			WO	9411955	A1	26-05-1994

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(74) Agents: WADSWORTH, Philip, R. et al.; Qualcomm Incorporated, 5775 Morehouse Drive, San Diego, CA 92121-1714 (US).

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(54) Title: METHOD AND APPARATUS FOR DEMODULATING SIGNALS PROCESSED IN A TRANSMIT DIVERSITY MODE

(57) Abstract: Demodulator architectures for processing a received signal in a wireless communications system. The demodulator includes a number of correlators coupled to a combiner. Each correlator typically receives and despreads input samples (which are generated from the received signal) with a respective despreading sequence to provide despread samples. Each correlator then decovers the despread samples to provide decovered "half-symbols" and further demodulates the decovered half-symbols with pilot estimates to generate correlated symbols. The decovering is performed with a Walsh symbol having a length (T) that is half the lenght (2T) of a Walsh symbol used to cover the data symbols in the transmitted signal.The combiner selectively combines correlated symbols from the assigned correlators to provide demodualted symbols. One or more correlators can be assigned to process one or more instances of each transmiteed signal. The pilot estimates used within each assigned correlator to demodulate the decovered half-symbols are generated based on the signal instance being prcessed by that correlator.

WO 01/97400 A2

METHOD AND APPARATUS FOR DEMODULATING SIGNALS PROCESSED IN A TRANSMIT DIVERSITY MODE

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to data communications. More particularly, the present invention relates to method and apparatus for efficiently demodulating signals that have been processed and transmitted in a diversity mode.

II. Description of the Related Art

In a typical digital communications system, data is processed, modulated, and conditioned at a transmitter unit to generate a modulated signal that is then transmitted to one or more receiver units. The data processing may include, for example, formatting the data into a particular frame format, encoding the formatted data to provide error detection and/or correction at the receiver unit, channelizing (i.e., covering) the coded data, and spreading the channelized data over the system bandwidth. The data processing is typically defined by the system or standard being implemented.

At the receiver unit, the transmitted signal is received, conditioned, demodulated, and digitally processed to recover the transmitted data. The processing at the receiver unit is complementary to that performed at the transmitter unit and may include, for example, despreading the received samples, decovering the despread samples to generate decovered symbols, and decoding the decovered symbols.

In some communications systems, data is processed and redundantly transmitted over two (or possibly more) antennas to provide transmit diversity. The processing may include, for example, covering the data for each antenna with a particular channelization code (e.g., a particular Walsh symbol). In some systems, the data for one or more antennas may also be reordered prior to the channelization. Due to multipath and other phenomena, the transmitted signals may experience different path conditions and may arrive at the receiver unit at different times. If the transmit antennas are spaced sufficiently far apart, then the received signals from the antennas tend to fade independently. Each transmitted signal may also reach the receiver unit via multiple signal paths.

The receiver unit is then required to receive, track, and process one or more instances of each transmitted signal, and to combine the results from the processed signal instances to recover the transmitted data. On the downlink, the processing typically includes tracking a pilot that has been transmitted along with the data, and using the recovered pilot to demodulate data samples.

The signal processing (e.g., demodulation) to process multiple transmitted signals, and multiple instances of such signals, can be complicated. Moreover, transmit diversity is typically provided on the downlink, and user terminals are required to support such a mode. The user terminals are typically more impacted by complexity and costs considerations. Therefore, techniques that can be used to efficiently demodulate signals that have been processed and transmitted in a diversity mode are highly desirable.

SUMMARY OF THE INVENTION

The present invention provides demodulator architectures, demodulators, and receiver units for processing signals that have been processed and transmitted in a transmit diversity mode. When operating in the transmit diversity mode, data symbols are typically covered with a channelization code (e.g., a Walsh symbol) having a length (2T) that is twice the length (T) of the channelization code used to cover the data symbols in the non-transmit diversity mode. The demodulator architectures of the invention exploit this property and perform partial processing (e.g., despreading, decovering, pilot demodulation, or a combination thereof) on each fraction of a channelization symbol period of 2T. The processed "partial-symbols" are then appropriately combined to generate the demodulated symbols. By performing partial processing on each fraction (e.g., each half) of the symbol period of 2T, computational complexity and costs can be reduced and performance may be improved. For example, with the present invention, the pilot demodulation in each assigned correlator (i.e., finger) can be performed based only on pilot estimates generated by that correlator, whereas conventional techniques may require pilots from multiple correlators. Other advantages are described below.

An embodiment of the invention provides a demodulator for processing a received signal in a wireless communications system. The demodulator includes a number of correlators coupled to a combiner. Each correlator typically receives and despreads input samples with a respective despreading sequence to provide despread samples. The input samples are generated from the received signal. Each correlator then decovers the despread samples to

provide decovered "partial-symbols" and further demodulates the decovered partial-symbols with pilot estimates to generate correlated symbols. The decovering is performed with a channelization symbol (e.g., a Walsh symbol) having a length (e.g., T) that is a fraction (e.g., half) the length 2T of the channelization symbol used to cover the data symbols in the received signal. The combiner receives and selectively combines correlated symbols from the assigned correlators to provide demodulated symbols.

In the transmit diversity mode of a CDMA-2000 or W-CDMA standard (which are identified below), the received signal includes a pair of signals transmitted from a pair of antennas. One or more correlators can then be assigned to process at one or more instances of each transmitted signal. Each assigned correlator processes the received signal to recover pilot estimates corresponding to the signal instance being processed. The pilot estimates are then used within the assigned correlator to demodulate the decovered partial-symbols.

A specific embodiment of the invention provides a demodulator that includes a number of correlators coupled to a combiner. Each correlator typically includes a despreader, a decover element, a complex multiplier, and a switch coupled in series. The despreader receives and despreads input samples with a particular despreading sequence to provide despread samples, and the decover element decovers the despread samples to provide pairs of decovered half-symbols. The decovering is performed with a Walsh symbol W having a length (T) that is half the length (2T) of a Walsh symbol W_{STS} used to cover the data in the received signal. (Space-Time Spreading (STS) is a transmit diversity mode defined by the CDMA-2000 standard.) One pair of decovered half-symbols is provided for each Walsh symbol period of 2T. The complex multiplier then demodulates the decovered half-symbols with a pilot recovered by the correlator to provide demodulated half-symbols.

The switch provides a first combination of decovered half-symbols for each Walsh symbol period of 2T in a first (e.g., even) symbol stream and a second combination of decovered half-symbols for each Walsh symbol period of 2T in a second (e.g., odd) symbol stream. The combiner combines the first symbol streams from the correlators to provide a first (even) output symbol stream, and further combines the second symbol streams from the correlators to provide a second (odd) output symbol stream.

In one design of this specific embodiment, the multiplier in each correlator performs a dot product and a cross product between the decovered half-symbols and the pilot to provide "dot" symbols and "cross" symbols,

respectively. The combiner can then be designed to selectively combine the dot and cross symbols for each Walsh symbol period of 2T to provide the demodulated symbols for the first and second output symbol streams.

Another specific embodiment of the invention provides a demodulator that also includes a number of correlators coupled to a combiner. Each correlator typically includes a despreader, a decover element, first and second summers, and first and second complex multipliers. The despreader receives and despreads input samples with a particular despreading sequence to provide despread samples, and the decover element decovers the despread samples to provide pairs of decovered half-symbols. Again, the decovering is performed with a Walsh symbol W having a length (T) that is half the length (2T) of a Walsh symbol W_{STS} used to cover data symbols in the received signal, and one pair of decovered half-symbols is generated for each Walsh symbol period of 2T.

Each correlator typically further includes a switch coupled to the decover element. The switch provides decovered half-symbols corresponding to the first half of the Walsh symbol period of 2T to a first output and decovered half-symbols corresponding to the second half of the Walsh symbol period of 2T to a second output. Each summer then operatively couples to the outputs of the switch and combines each pair of decovered half-symbols in a particular manner to provide a decovered symbol. Each multiplier then demodulates the decovered symbols from a respective summer with a respective pilot to provide a respective symbol stream.

The combiner receives the first and second symbol streams from the first and second multipliers, respectively, of each assigned correlator, combines the first symbol streams from all assigned correlators to provide a first output symbol stream, and further combines the second symbol streams from all assigned correlators to provide a second output symbol stream.

Another embodiment of the invention provides a method for processing a received signal in a wireless communications system. The received signal can include a pair of signals transmitted from a pair of antennas. In accordance with the method, input samples are generated from the received signal. At least one signal instance of each transmitted signal is then processed to provide correlated symbols. The processing for each signal instance typically includes despreading the input samples with a particular despreading sequence associated with the signal instance being processed to provide despread samples, decovering the despread samples to generate decovered partial-symbols (e.g., half-symbols), and demodulating the decovered partial-symbols

with pilot estimates to generate the correlated symbols for the signal instance. Again, the decovering is performed with a Walsh symbol W having a length (e.g., T) that is a fraction of (e.g., half) the length (2T) of a Walsh symbol W_{STS} used to cover the data in the received signal. The correlated symbols for all signal instances being processed are then selectively combined to provide demodulated symbols.

The invention further provides other demodulator architectures, correlators, demodulators, receiver units, and methods to process signals that have been processed and transmitted in a transmit diversity mode

BRIEF DESCRIPTION OF THE DRAWINGS

The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1 is a simplified block diagram of a communications system in which the present invention may be implemented;

FIG. 2 is a block diagram of a modulator that can be used to process a downlink data transmission in a transmit diversity mode in accordance with CDMA-2000 standard;

FIG. 3 is a diagram of a complex multiplier;

FIG. 4 is a block diagram of a conventional demodulator architecture that can be used to demodulate a downlink data transmission that has been processed in the transmit diversity mode; and

FIGS. 5, 6, and 7 are block diagrams of three specific embodiments of a demodulator architecture of the invention, which are also capable of demodulating the downlink data transmission that has been processed in the transmit diversity mode.

DETAILED DESCRIPTION OF THE SPECIFIC EMBODIMENTS

FIG. 1 is a simplified block diagram of an embodiment of a communications system 100 in which the present invention may be implemented. At a transmitter unit 110, traffic data is sent, typically in frames or packets, from a data source 112 to a transmit (TX) data processor 114 that formats, encodes, and processes the data. TX data processor 114 typically further processes signaling and pilot data, which is then combined (e.g., added,

or time division multiplexed) with the processed traffic data to generate composite data. A modulator (MOD) 116 then receives, channelizes (i.e., covers), and spreads the composite data to generate symbols that are then converted to analog signals. The analog signals are filtered, (quadrature) modulated, amplified, and upconverted by a transmitter (TMTR) 118 to generate one or more modulated signals, which are then transmitted via respective antennas 120 to one or more receiver units.

At a receiver unit 130, the transmitted signals are received by an antenna 132 and provided to a receiver (RCVR) 134. Within receiver 134, the received signal is amplified, filtered, downconverted, quadrature demodulated, and digitized to provide inphase (I) and quadrature (Q) samples. A demodulator (DEMOD) 136 then receives, despreads, and decovers the samples to generate decovered symbols. In certain designs, demodulator 136 further demodulates the decovered symbols with pilot estimates to generate demodulated symbols. The demodulated symbols are then decoded and processed by a receive (RX) data processor 138 to recover the transmitted data. The despreading, decovering, decoding, and processing at receiver unit 130 are performed complementary to the spreading, covering, coding, and processing at transmitter unit 110. The recovered data is then provided to a data sink 140.

The signal processing described above supports transmissions of voice, video, packet data, messaging, and other types of communication in one direction. A bi-directional communications system supports two-way data transmission. However, the signal processing for the other direction is not shown in FIG. 1 for simplicity.

Communications system 100 can be a code division multiple access (CDMA) system, a time division multiple access (TDMA) communications system (e.g., a GSM system), a frequency division multiple access (FDMA) communications system, or other multiple access communications system that supports voice and data communication between users over a terrestrial link.

The use of CDMA techniques in a multiple access communications system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM". Another specific CDMA system is disclosed in U.S. Patent Application Serial No. 08/963,386, entitled "METHOD AND APPARATUS FOR HIGH RATE PACKET DATA TRANSMISSION," filed

November 3, 1997. These patents and patent application are assigned to the assignee of the present invention and incorporated herein by reference.

CDMA systems are typically designed to conform to one or more standards such as the "TIA/EIA/IS-95-A Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System" (hereinafter referred to as the IS-95-A standard), the "TIA/EIA/IS-98 Recommended Minimum Standard for Dual-Mode Wideband Spread Spectrum Cellular Mobile Station" (hereinafter referred to as the IS-98 standard), the standard offered by a consortium named "3rd Generation Partnership Project" (3GPP) and embodied in a set of documents including Document Nos. 3G TS 25.211, 3G TS 25.212, 3G TS 25.213, and 3G TS 25.214 (hereinafter referred to as the W-CDMA standard), and the "TR-45.5 Physical Layer Standard for cdma2000 Spread Spectrum Systems" (hereinafter referred to as the CDMA-2000 standard). New CDMA standards are continually proposed and adopted for use. These CDMA standards are incorporated herein by reference.

FIG. 2 is a block diagram of modulator 116, which can be used to process a downlink data transmission in a Space-Time Spreading transmit diversity mode in accordance with the CDMA-2000 standard (hereinafter referred to as the STS mode). In the STS mode of the CDMA-2000 standard, the data symbols Y to be transmitted are provided to a demultiplexer (DEMUX) 208 and demultiplexed into two complex symbol streams, Y_{even} and Y_{odd}, which are then provided to modulators 210a and 210b. The even complex symbol stream Y_{even} comprises the even inphase symbol stream Y_{I1} and the even quadrature symbol stream Y_{Q1}. Similarly, the odd complex symbol stream Y_{odd} comprises the odd inphase symbol stream Y_{I2} and the odd quadrature symbol stream Y_{Q2}. The even symbol streams comprise "even" indexed data symbols and the odd symbol streams comprise "odd" indexed data symbols. Each modulator 210 performs channelization (i.e., covering) and spreading of the even and odd symbol streams and provides a complex output symbol stream S for a respective antenna.

In the non-transmit diversity (non-TD) mode of the CDMA-2000 standard, complex data symbols are transmitted serially, with each data symbol having a signaling period of T. In the STS mode, two complex data symbols are transmitted in parallel over two antennas, with each data symbol having a signaling period of 2T. As defined by the CDMA-2000 standard, within each modulator 210, one of the complex symbol streams (even or odd) is covered with a Walsh symbol W_{STS} having a length of 2T, and the other complex symbol

stream (odd or even) is covered with a complementary Walsh symbol $\overline{W}_{STS}$ having a length of 2T.

Within modulator 210a, the even and odd complex symbol streams, Y_{even} and Y_{odd}, are provided to symbol repeaters 212a and 212b, respectively. In the STS mode, each symbol repeater 212 repeats each received data symbol once to double the signaling period from T to 2T. The symbol streams from symbol repeaters 212a and 212b are then provided to cover elements 214a and 214b, respectively, which cover the data symbols with a channelization code associated with the physical channel used for the data transmission. In the STS mode, the channelization code for cover element 214a is the Walsh symbol W_{STS} having a length of 2T, and the channelization code for cover element 214b is the complementary Walsh symbol $\overline{W}_{STS}$ having the same length of 2T. Each cover element 214 covers (e.g., multiplies) each received data symbol with the Walsh symbol W_{STS} or $\overline{W}_{STS}$ in a manner known in the art.

In the STS mode, the complex symbols from cover element 214b are provided to a complex conjugator 216a that conjugates each received symbol. The conjugated symbols from complex conjugator 216a are then provided to a summer 218a and subtracted from the symbols from cover element 214a to provide complex covered symbols. Each complex covered symbol thus includes a pair of data symbols that have been covered with the Walsh symbols W_{STS} and $\overline{W}_{STS}$. The signal processing in the STS mode provides diversity in the transmitted signals, which can result in improved performance.

In the embodiment shown in FIG. 2, the complex covered symbols from summer 218a are provided to a phase rotator 222a. In an embodiment, phase rotator 222a provides a phase rotation of the received complex symbols (e.g., in 90° increments) when enabled by a control signal ROTATE. For example, if the received complex symbols are expressed as $I_C + jQ_C$, phase rotator 222a can provide 90° phase rotation of the complex symbols, which can then be expressed as $-Q_C + jI_C$. The phase rotation allows modulator 210a to account (i.e., compensate) for phase shifts in the modulated signal due to switching or adjustments in the subsequent signal conditioning circuitry within transmitter 118.

A complex multiplier 224a then receives the phase rotated complex symbol stream from phase rotator 222a and a complex spreading sequence PN, spreads the complex symbol stream with the complex spreading sequence, and provides a complex output symbol stream S_1. The complex spreading sequence PN is generated in a manner defined by the particular CDMA system

or standard being implemented. For the CDMA-2000 system, the complex spreading sequence PN is generated by multiplying the short PN sequences, IPN and QPN, assigned to the transmitting base station with the long PN sequence assigned to the receiving user terminal for which the data transmission is destined.

FIG. 3 is a diagram of a complex multiplier 300 that can be used to implement each complex multiplier 224 in FIG. 2. Complex multiplier 300 performs a complex multiply of the complex data symbols, $D_I + jD_Q$, with the complex spreading sequence, $PN_I + jPN_Q$, to provide complex spread output symbols, $S_I + jS_Q$.

Within complex multiplier 300, the inphase data symbols D_I are provided to multipliers 312a and 312b, and the quadrature data symbols D_Q are provided to multipliers 312c and 312d. Each of the multipliers 312a and 312d also receives the inphase spreading sequence PN_I, and each of multipliers 312b and 312c also receives the quadrature spreading sequence PN_Q. Each multiplier 312 multiplies the received data symbols with the received spreading sequence and provides respective spread symbols. A summer 314a receives and subtracts the output from multiplier 312c from the output from multiplier 312a to provide the inphase output symbols S_I. A summer 314b receives and combines the outputs from multipliers 312b and 312d to provide the quadrature output symbols S_Q.

Referring back to FIG. 2, modulator 210b is configured similar to modulator 210a, with three differences. First, in modulator 210b, the complementary Walsh symbol $\overline{W}_{STS}$ is used to cover the even complex symbol stream Y_{even}, and the Walsh symbol W_{STS} is used to cover the odd complex symbol stream Y_{odd}. Second, complex conjugator 216b couples to the output of cover element 214c (i.e., the processing path for the even complex symbol stream Y_{even}). And third, the signs for the inputs of summer 218b are different than the signs for the inputs of summer 216a in modulator 210a.

The processing performed by modulator 116 can be described as follows. Initially, the even and odd complex symbol streams can be expressed as:

$$Y_{even} = Y_{I1} + j\,Y_{Q1} \text{ , and} \qquad \text{Eq (1)}$$

$$Y_{odd} = Y_{I2} + j\,Y_{Q2} \text{ .} \qquad \text{Eq (2)}$$

As defined by the CDMA-2000 standard, the Walsh symbols W_{STS} and $\overline{W}_{STS}$ are used to cover the even and odd complex symbol streams. Each of these Walsh

symbols has a length of 2T and can be generated from a Walsh symbol W of length T as follows:

$$W_{STS} = WW \text{, and} \qquad \text{Eq (3)}$$

$$\overline{W}_{STS} = W\overline{W} \text{,}$$

where $\overline{W} = -W$.

If only the data symbols and the covering are considered (i.e., ignoring the PN spreading, phase rotation, transmit gain, pulse shaping, and other signal processing), the complex output symbol stream for antenna 1 can be expressed as:

$$S_1 = Y_{even}WW - Y^*_{odd}W\overline{W} \text{,} \qquad \text{Eq (4)}$$

where the asterisk (*) denotes a complex conjugate operation. Similarly, the complex output symbol stream for antenna 2 can be expressed as:

$$S_2 = Y^*_{even}W\overline{W} + Y_{odd}WW \text{.} \qquad \text{Eq (5)}$$

The complex output symbol streams, S_1 and S_2, are subsequently provided to two respective processing paths in transmitter 118. Each processing path filters the inphase and quadrature symbol streams, S_I and S_Q, of the complex symbol stream S, modulates the filtered S_I stream with an inphase carrier signal $\cos(\omega_c t)$, modulates the filtered S_Q stream with a quadrature carrier signal $\sin(\omega_c t)$, sums the two modulated components, and further conditions the resultant signal to generate a modulated signal. In the STS mode, two modulated signals are generated based on two complex symbol streams S_1 and S_2, and are transmitted from two antennas.

Typically, distinct (i.e., orthogonal) pilots are sent on respective transmit antennas. For example, for the CDMA-2000 system, an unmodulated pilot (using Walsh code 0, 64) is sent on the common antenna and a modulated diversity pilot (using Walsh code 16, 128) is sent on the diversity antenna. The pilots are selected to be orthogonal so that the amplitude and phase of one or both signals transmitted from the respective antennas can be recovered.

The downlink signal processing for the CDMA-2000 standard is described in further detail in the CDMA-2000 standard, and by M. Buehrer et al. in a paper entitled "Proposed Text for Space Time Spreading (STS) v0.3," dated 1999, and incorporated herein by reference. This paper was adopted into the CDMA-2000 standard by the 3GPP2 standard body.

FIG. 4 is a block diagram of a conventional demodulator architecture 400 capable of demodulating a downlink data transmission that has been processed in the STS mode of the CDMA-2000 standard. In the STS mode, the received signal includes two modulated signals that have been transmitted from two transmit antennas. The signal from each transmit antenna typically experiences different path conditions, due to the spatial separation of the transmit antennas, and arrives at the receiver unit distorted by the particular path conditions. At the receiver unit, two or more correlators (i.e., fingers) are used to receive and demodulate the two transmitted signals. The demodulated symbols from the correlators are then combined to recover the transmitted symbols.

Initially, the received signal is conditioned (e.g., amplified, filtered, downconverted, quadrature demodulated, and so on) and digitized to provide a complex sample stream comprised of inphase samples I_{IN} and quadrature samples Q_{IN}. The complex sample stream is provided to each correlator assigned to process the received signal. Each correlator receives, tracks, and processes a respective instance (i.e., a particular multipath) of the signal from one of the transmit antennas.

As shown in FIG. 4, a correlator 410a is assigned to receive and process the signal from the first transmit antenna, and a correlator 410b is assigned to receive and process the signal from the second transmit antenna. Within correlator 410a, the complex received samples (i.e., $I_{IN} + jQ_{IN}$) are provided to a complex multiplier 412a that also receives a complex despreading sequence PN_1 (i.e., $PN_1 = PN_{I1} + jPN_{Q1}$) having a particular time offset assigned to correlator 410a and matching the time delay of the signal instance being processed. Complex multiplier 412a despreads the complex samples with the PN_1 sequence and provides the complex despread samples (i.e., $I_{D1} + jQ_{D1}$) to a decover element 414a. Decover element 414a decovers the complex received samples with the Walsh symbol W_{STS} and provides complex decovered symbols to each of the complex multipliers 420a and 420b. The decovering is achieved by multiplying the inphase (and quadrature) samples with the Walsh symbol W_{STS} and accumulating the results over the length (2T) of the Walsh symbol W_{STS} to provide inphase (and quadrature) decovered symbols.

Complex multiplier 420a then demodulates the complex decovered symbols with a conjugated complex pilot $\hat{h}_1^*$ (estimated from a pilot transmitted from a first transmit antenna) recovered by correlator 410a. Similarly, complex multiplier 420b demodulates the complex decovered symbols with a conjugated complex pilot $\hat{h}_2^*$ (estimated from a pilot transmitted from a second transmit antenna) recovered by correlator 410b. The output from complex multiplier

420a comprises the even complex symbol stream C_{even}^{1} that is provided to an accumulator 442a within a combiner 440. Similarly, the output from complex multiplier 420b comprises the odd complex symbol stream C_{odd}^{1} that is provided to an accumulator 442b within combiner 440.

Within correlator 410b, the complex received samples (i.e., $I_{IN} + jQ_{IN}$) are despread by a complex multiplier 412b with a complex despreading sequence PN_2 (i.e., $PN_2 = PN_{I2} + jPN_{Q2}$) having a particular time offset assigned to correlator 410b. The complex despread samples (i.e., $I_{D2} + jQ_{D2}$) are decovered by decover element 414b with the complementary Walsh symbol $\overline{W}_{STS}$ and conjugated by a complex conjugator 416. The conjugated symbols are then demodulated with the complex pilot $\hat{h}_2$ by a complex multiplier 420c, and further demodulated with the negative complex pilot $-\hat{h}_1$ by a complex multiplier 420d. The output from complex multiplier 420c comprises the even complex symbol stream C_{even}^{2} that is provided to accumulator 442a, and the output from complex multiplier 420d comprises the odd complex symbol stream C_{odd}^{2} that is provided to accumulator 442b.

Accumulator 442a combines the even complex symbol streams, C_{even}^{1} and C_{even}^{2}, from correlators 410a and 410b and provides the even output symbol stream C_{even} (i.e., $C_{even} = C_{I1} + jC_{Q1}$). Similarly, accumulator 442b combines the odd complex symbol streams, C_{odd}^{1} and C_{odd}^{2}, from correlators 410a and 410b and provides the odd output symbol stream C_{odd} ($C_{odd} = C_{I2} + jC_{Q2}$). The symbol streams C_{I1}, C_{Q1}, C_{I2}, and C_{Q2} are estimates of the symbol streams Y_{I1}, Y_{Q1}, Y_{I2}, and Y_{Q2}, respectively, generated within modulator 116 in FIG. 2 and expressed in equations (1) and (2).

Demodulator architecture 400 is described in further detail by A. Kogiantis et al. in a paper entitled "Downlink Improvement through Space-Time Spreading," dated August 5, 1999, and incorporated herein by reference. This paper was submitted to the 3GPP2 standard body for adoption into the CDMA-2000 standard.

Demodulator architecture 400 shown in FIG. 4 has several major disadvantages. First, sharing of information between correlators is required to perform the pilot demodulation. Each correlator 410 performs two complex multiplications to achieve the pilot demodulation. The first complex multiplication is performed between the decovered symbols and the complex pilot estimated by that correlator. The second complex multiplication is performed between the decovered symbols and the complex pilot estimated by the other correlator. Demodulator architecture 400 can be modified to share

decovered symbols instead of pilot estimates. However, in both cases, the need to share information between correlators is highly undesirable in many circuit designs. Additional circuitry would likely be required to coordinate the sharing of information, which would lead to increased complexity and costs.

Second, if more than one multipath of any of the transmitted signals is processed, it is necessary to pair up correlators with the same path delay to perform the pilot demodulation. This requirement imposes constraints on the use of the correlators and requires coordination between the correlators.

Consequently, as a result of these disadvantages, system performance may be compromised by the use of demodulator architecture 400.

FIG. 5 is a block diagram of a specific embodiment of a demodulator architecture 500 of the invention, which is capable of demodulating a downlink data transmission that has been processed in the STS mode of the CDMA-2000 standard. Initially, the received signal is conditioned and digitized to provide a complex sample stream that is provided to each of correlators 510a and 510b. Each correlator 510 receives, tracks, and demodulates a signal transmitted from one of the transmit antennas.

Within correlator 510a, the complex received samples (i.e., $I_{IN} + jQ_{IN}$) are despread by a complex multiplier 512a with a complex despreading sequence PN_1 having a particular time offset assigned to correlator 510a. The complex despread samples (i.e., $I_{D1} + jQ_{D1}$) are then decovered by decover element 514a with a Walsh symbol W having a length of T to provide decovered "half-symbols". The decovering is achieved by multiplying the inphase (and quadrature) samples by the Walsh symbol W and accumulating the resultant samples over the length (T) of the Walsh symbol W.

Referring back to FIG. 2, in the STS mode, each data symbol is covered by the Walsh symbol W_{STS} or $\overline{W}_{STS}$ having a length of 2T, which corresponds to one STS symbol period. Also, referring to equation (3), the Walsh symbols W_{STS} and $\overline{W}_{STS}$ are generated by combining the Walsh symbol W and the complementary Walsh symbol $\overline{W}$. The Walsh symbols W and $\overline{W}$ each has a length of T, which is half the length of the Walsh symbols W_{STS} and $\overline{W}_{STS}$. Each decovered half-symbol from decover element 514 thus corresponds to only half of the STS symbol period.

The complex decovered half-symbols from decover element 514a are provided to a switch 520a. Switch 520a provides the decovered half-symbols corresponding to the first half of the STS symbol period (switch 520a in position A) to a delay element 522a and the decovered half-symbols corresponding to the second half of the STS symbol period (switch 520a in position B) to summers

524a and 524b. Switch 520a can be implemented with a demultiplexer, registers, latches, or some other element. Delay element 522a delays the received half-symbols and provides the delayed half-symbols to summers 524a and 524b. The delay is selected such that the decovered half-symbols for each STS symbol period are aligned in time at the inputs of each of summers 524a and 524b.

For each STS symbol period of 2T (i.e., the length of the Walsh symbols W_{STS} and $\overline{W}_{STS}$) and after the decovered half-symbol corresponding to the second half of the STS symbol period has been received, summer 524a sums the two received half-symbols and provides the decovered symbol to a complex multiplier 528a. Similarly, for each STS symbol period, summer 524b subtracts the half-symbol received from switch 520a from the half-symbol received from delay element 522a and provides the decovered symbol to a complex conjugator 526a. Complex conjugator 526a conjugates the received symbols and provides the conjugated symbols to a complex multiplier 528b.

Complex multiplier 528a demodulates the complex decovered symbols from summer 524a with a conjugated complex pilot $\hat{h}_1^*$ recovered by correlator 510a. Similarly, complex multiplier 528b demodulates the complex decovered symbols from complex conjugator 526a with the negated complex pilot $-\hat{h}_1$. The output from complex multiplier 528a comprises the even complex symbol stream C_{even}^1 that is provided to an accumulator 542a within a combiner 540, and the output from complex multiplier 528b comprises the odd complex symbol stream C_{odd}^1 that is provided to an accumulator 542b within combiner 540.

Correlator 510b performs similar processing as correlator 510a. Within correlator 510b, the complex received samples (i.e., $I_{IN} + jQ_{IN}$) are despread by a complex multiplier 512b with a complex despreading sequence PN_2 having a particular time offset assigned to correlator 510b. The complex despread samples are then decovered by decover element 514b with the Walsh symbol W to provide decovered half-symbols.

The complex decovered half-symbols from decover element 514b are provided to a switch 520b, which provides decovered half-symbols corresponding to the first half of the STS symbol period (switch 520b in position A) to a delay element 522b and decovered half-symbols corresponding to the second half of the STS symbol period (switch 520b in position B) to summers 524c and 524d. Delay element 522b delays the received half-symbols and provides the delayed half-symbols to summers 524c and 524d. Again, the delay is selected such that the decovered half-symbols for each STS symbol period are

time-aligned at the inputs of each of summers 524c and 524d. For each STS symbol period, summer 524c subtracts the half-symbol received from switch 520b from the half-symbol received from delay element 522b and provides the decovered symbol to a complex conjugator 526b, which conjugates the received symbol and provides the conjugated symbol to a complex multiplier 528c. For each STS symbol period, summer 524d sums the two received half-symbols and provides the decovered symbol to a complex multiplier 528d.

Complex multiplier 528c demodulates the complex decovered symbols from complex conjugator 526b with a complex pilot $\hat{h}_2$ recovered by correlator 510b. Similarly, complex multiplier 528d demodulates the complex decovered symbols from summer 524d with the conjugated complex pilot $\hat{h}_2^*$. The output from complex multiplier 528c comprises the even complex symbol stream C_{even}^2 that is provided to accumulator 542a, and the output from complex multiplier 528d comprises the odd complex symbol stream C_{odd}^2 that is provided to accumulator 542b.

Accumulator 542a combines the even complex symbol streams, C_{even}^1 and C_{even}^2, from correlators 510a and 510b and provides the even output symbol stream C_{even} (i.e., $C_{even} = C_{I1} + jC_{Q1}$). Similarly, accumulator 542b combines the odd complex symbol streams, C_{odd}^1 and C_{odd}^2, from correlators 510a and 510b and provides the odd output symbol stream C_{odd} (i.e., $C_{odd} = C_{I2} + jC_{Q2}$). The symbol streams C_{I1}, C_{Q1}, C_{I2}, and C_{Q2} are estimates of the symbol streams Y_{I1}, Y_{Q1}, Y_{I2}, and Y_{Q2}, respectively, generated within modulator 116 in FIG. 2.

The processing performed by demodulator architecture 500 can be analyzed by first characterizing the transmitted symbol streams. The transmitted symbol streams, S_1 and S_2, in the STS mode are expressed above in equations (4) and (5). The Walsh symbols W_{STS} and $\overline{W}_{STS}$ of length 2T can each be decomposed into a combination of Walsh symbols W and $\overline{W}$, each of length T. The transmitted symbols can be decomposed into a combination of half-symbols transmitted over the first time interval T_1 of the STS symbol period and half-symbols transmitted over the second time interval T_2 of the STS symbol period.

The transmitted symbols for the first antenna in equation (4) can be expressed as:

$$
\begin{aligned}
S_1 &= S_1^{T1},\ S_1^{T2} \quad , \\
S_1^{T1} &= Y_{even} W - Y_{odd}^{*} W \quad , \text{ and} \\
S_1^{T2} &= Y_{even} W + Y_{odd}^{*} W \quad .
\end{aligned}
\qquad \text{Eq (6)}
$$

Similarly, the transmitted symbols for the second antenna in equation (5) can be expressed as:

$$
\begin{aligned}
S_2 &= S_2^{T1},\ S_2^{T2} \quad , \\
S_2^{T1} &= Y_{even}^{*} W + Y_{odd} W \quad , \text{ and} \\
S_2^{T2} &= -Y_{even}^{*} W + Y_{odd} W \quad .
\end{aligned}
\qquad \text{Eq (7)}
$$

The signals from the first and second transmit antennas are received with random amplitudes and phases given by the complex values h_1 and h_2, respectively. The values h_1 and h_2 characterize the path loss and multipath fading experienced by the transmitted signals. If the noise is ignored, the composite received signal can be expressed as:

$$
\begin{aligned}
R &= S_1 h_1,\ S_2 h_2 = R^{T1},\ R^{T2} \quad , \\
R^{T1} &= S_1^{T1} h_1 + S_2^{T1} h_2 \quad , \qquad \text{and} \\
R^{T2} &= S_1^{T2} h_1 + S_2^{T2} h_2 \quad ,
\end{aligned}
\qquad \text{Eq (8)}
$$

where R^{T1} and R^{T2} represent the received symbol waveforms for the first and second time intervals, T_1 and T_2, respectively, of the STS symbol period. The even complex symbol streams C_{even}^{1} and C_{even}^{2} from correlators 510a and 510b, respectively, can be computed as:

$$
\begin{aligned}
C_{even}^{1} &= \left(\langle R^{T1}, W \rangle + \langle R^{T2}, W \rangle \right) \hat{h}_1^{*} \\
&= \left(\langle \left(S_1^{T1} h_1 + S_2^{T1} h_2 \right), W \rangle + \langle \left(S_1^{T2} h_1 + S_2^{T2} h_2 \right), W \rangle \right) \hat{h}_1^{*} \\
&= N \left(\left(\left(Y_{even} - Y_{odd}^{*} \right) + \left(Y_{even} + Y_{odd}^{*} \right) \right) h_1 + \left(\left(Y_{even}^{*} + Y_{odd} \right) + \left(- Y_{even}^{*} + Y_{odd} \right) \right) h_2 \right) \hat{h}_1^{*} \\
&= 2N \left(Y_{even} h_1 \hat{h}_1^{*} + Y_{odd} h_2 \hat{h}_1^{*} \right)
\end{aligned}
$$

Eq (9)

$$
\begin{aligned}
C_{even}^{2} &= \left(\left\langle R^{T1}, W\right\rangle - \left\langle R^{T2}, W\right\rangle\right)^{*} \hat{h}_2 \\
&= \left(\left\langle \left(S_1^{T1} h_1 + S_2^{T1} h_2\right), W\right\rangle - \left\langle \left(S_1^{T2} h_1 + S_2^{T2} h_2\right), W\right\rangle\right)^{*} \hat{h}_2 \\
&= N\left(\left(\left(Y_{even} - Y_{odd}^{*}\right) - \left(Y_{even} + Y_{odd}^{*}\right)\right)^{*} h_1^{*} + \left(\left(Y_{even}^{*} + Y_{odd}\right) - \left(-Y_{even}^{*} + Y_{odd}\right)\right)^{*} h_2^{*}\right)\hat{h}_2 \\
&= 2N\left(-Y_{odd}\, h_1^{*}\, \hat{h}_2 + Y_{even}\, h_2^{*}\, \hat{h}_2\right)
\end{aligned}
$$

Eq (10)

where $\left\langle R^{T1}, W\right\rangle$ denotes the decovering of the symbol waveform R^{T1} by the first correlator with the Walsh symbol W, 2N represents the length of the Walsh symbols W_{STS} and $\overline{W}_{STS}$ (in chips), and $(AB)^{*} = A^{*}\, B^{*}$. Similarly, the odd complex symbol streams C_{odd}^{1} and C_{odd}^{2} from correlators 510a and 510b, respectively, can be computed as:

$$
\begin{aligned}
C_{odd}^{1} &= -\left(\left\langle R^{T1}, W\right\rangle - \left\langle R^{T2}, W\right\rangle\right)^{*} \hat{h}_1 \\
&= -\left(\left\langle \left(S_1^{T1} h_1 + S_2^{T1} h_2\right), W\right\rangle - \left\langle \left(S_1^{T2} h_1 + S_2^{T2} h_2\right), W\right\rangle\right)^{*} \hat{h}_1 \\
&= -N\left(\left(\left(Y_{even} - Y_{odd}^{*}\right) - \left(Y_{even} + Y_{odd}^{*}\right)\right)^{*} h_1^{*} + \left(\left(Y_{even}^{*} + Y_{odd}\right) - \left(-Y_{even}^{*} + Y_{odd}\right)\right)^{*} h_2^{*}\right)\hat{h}_1 \\
&= 2N\left(Y_{odd}\, h_1^{*}\, \hat{h}_1 - Y_{even}\, h_2^{*}\, \hat{h}_1\right)
\end{aligned}
$$

Eq (11)

$$
\begin{aligned}
C_{odd}^{2} &= \left(\left\langle R^{T1}, W\right\rangle + \left\langle R^{T2}, W\right\rangle\right) \hat{h}_2^{*} \\
&= \left(\left\langle \left(S_1^{T1} h_1 + S_2^{T1} h_2\right), W\right\rangle + \left\langle \left(S_1^{T2} h_1 + S_2^{T2} h_2\right), W\right\rangle\right) \hat{h}_2^{*} \\
&= N\left(\left(\left(Y_{even} - Y_{odd}^{*}\right) + \left(Y_{even} + Y_{odd}^{*}\right)\right) h_1 + \left(\left(Y_{even}^{*} + Y_{odd}\right) + \left(-Y_{even}^{*} + Y_{odd}\right)\right) h_2\right)\hat{h}_2^{*} \\
&= 2N\left(Y_{even}\, h_1\, \hat{h}_2^{*} + Y_{odd}\, h_2\, \hat{h}_2^{*}\right)
\end{aligned}
$$

Eq (12)

The even complex symbol stream C_{even} from combiner 542a and the odd complex symbol stream C_{odd} from combiner 542b can be expressed as:

$$
\begin{aligned}
C_{even} &= C_{even}^{1} + C_{even}^{2} \quad , \\
&= 2N\left(Y_{even}\, h_1\, \hat{h}_1^{*} + Y_{odd}\, h_2\, \hat{h}_1^{*}\right) + 2N\left(-Y_{odd}\, h_1^{*}\, \hat{h}_2 + Y_{even}\, h_2^{*}\, \hat{h}_2\right) \quad , \text{Eq (13)} \\
&= 2N\left(Y_{even}\left(h_1\, \hat{h}_1^{*} + h_2^{*}\, \hat{h}_2\right) + Y_{odd}\left(h_2\, \hat{h}_1^{*} - h_1^{*}\, \hat{h}_2\right)\right) \quad ,
\end{aligned}
$$

$$
\begin{aligned}
C_{odd} &= C_{odd}^{1} + C_{odd}^{2} \quad , \\
&= 2N\left(Y_{odd}\, h_1^{*}\, \hat{h}_1 - Y_{even}\, h_2^{*}\, \hat{h}_1\right) + 2N\left(Y_{even}\, h_1\, \hat{h}_2^{*} + Y_{odd}\, h_2\, \hat{h}_2^{*}\right) \quad , \text{Eq (14)} \\
&= 2N\left(Y_{odd}\left(h_1^{*}\hat{h}_1 + h_2\hat{h}_2^{*}\right) + Y_{even}\left(h_1\, \hat{h}_2^{*} - h_2^{*}\, \hat{h}_1\right)\right) \quad .
\end{aligned}
$$

In each of equations (13) and (14), the first term is the desired signal component and the second term is the undesired component due to cross-talk. If the pilot estimates are accurate (i.e., $\hat{h}_1 = h_1$ and $\hat{h}_2 = h_2$), then equations (13) and (14) simplify as follows:

$$C_{even} = 2N\ Y_{even}\left(|h_1|^2 + |h_2|^2\right)\ , \qquad \text{Eq (15)}$$

$$C_{odd} = 2N\ Y_{odd}\left(|h_1|^2 + |h_2|^2\right)\ . \qquad \text{Eq (16)}$$

Demodulator architecture 500 can recover the transmitted symbols if one transmit antenna should fail to operate or if the signal transmitted from one of the antennas experiences a deep fade. As an example, if the second transmit antenna should fail, the received symbol stream can be expressed as:

$$\begin{aligned} R &= S_1 h_1\ , \\ R^{T1} &= S_1^{T1} h_1\ , \text{ and} \\ R^{T2} &= S_1^{T2} h_1\ . \end{aligned} \qquad \text{Eq (17)}$$

At the receiver unit, one correlator can be used to receive and process the transmitted signal. The even and odd complex symbol streams, C_{even} and C_{odd}, from the assigned correlator can be expressed as:

$$\begin{aligned} C_{even}^1 &= \left(\langle R^{T1}, W\rangle + \langle R^{T2}, W\rangle\right)\hat{h}_1^*\ , \\ &= \left(\langle (S_1^{T1} h_1), W\rangle + \langle (S_1^{T2} h_1), W\rangle\right)\hat{h}_1^*\ , \\ &= N\left(\left((Y_{even} - Y_{odd}^*) + (Y_{even} + Y_{odd}^*)\right)h_1\right)\hat{h}_1^*\ , \\ &= 2N\left(Y_{even}\, h_1\, \hat{h}_1^*\right)\ . \end{aligned} \qquad \text{Eq (18)}$$

$$\begin{aligned} C_{odd}^1 &= -\left(\langle R^{T1}, W\rangle - \langle R^{T2}, W\rangle\right)^* \hat{h}_1 \\ &= -\left(\langle (S_1^{T1} h_1), W\rangle - \langle (S_1^{T2} h_1), W\rangle\right)^* \hat{h}_1 \\ &= -N\left(\left((Y_{even} - Y_{odd}^*) - (Y_{even} + Y_{odd}^*)\right)^* h_1^*\right)\hat{h}_1 \\ &= 2N\left(Y_{odd}\, h_1^*\, \hat{h}_1\right) \end{aligned} \qquad \text{Eq (19)}$$

Again, if the pilot estimate is accurate (i.e., $\hat{h}_1 = h_1$), then equations (18) and (19) simplify as follows:

$$C^1_{even} = 2N\ Y_{even}\left(|h_1|^2\right)\ ,$$

$$C^1_{odd} = 2N\ Y_{odd}\left(|h_1|^2\right)\ .$$

Demodulator architecture 500 shown in FIG. 5 provides a number of advantages over demodulator architecture 400 shown in FIG. 4. These advantages can result in a simplified design, reduced costs, improved performance, some other advantages, or a combination thereof. Some of these advantages are described below.

First, demodulator architecture 500 does not require the sharing of pilot estimates and data symbols between correlators. Each correlator receives, processes, and demodulates the received sample stream with its own pilot estimate. The autonomous design for the correlators eliminates the need to transfer information between correlators and simplifies the design of the receiver unit that uses demodulator architecture 500.

Second, demodulator architecture 500 does not require correlators to be paired up. This allows for flexibility in assigning correlators to the strongest signal instances, which can lead to improved performance.

Third, demodulator architecture 500 does not require synchronization of the pilots of paired correlators that have unequal path delays. This feature results from the ability of each correlator to operate independently based on the received samples and its own pilot estimate. In contrast, since the correlators are operated in pairs in demodulator architecture 400, the pilots needs to be properly aligned in time to account for any delays between the signal instances being processed by the pair of correlators.

Fourth, demodulator architecture 500 allows for reception of the transmitted symbols if one of the transmit antennas should fail to operate or is in a deep fade. In contrast, demodulator architecture 400 can only recover half of the transmitted symbol should one transmit antenna fail. Demodulator architecture 500 can be used to provide a more robust and reliable communication.

FIG. 6 is a block diagram of another specific embodiment of a demodulator architecture 600 of the invention, which is also capable of demodulating a downlink data transmission that has been processed in the STS mode of the CDMA-2000 standard. The complex sample stream is provided to correlators 610a and 610b, with each correlator 610 operated to receive, track, and demodulate a signal transmitted from one of the transmit antennas.

Within correlator 610a, the complex received samples are despread by a complex multiplier 612a with a despreading sequence PN_1 and decovered by a decover element 614a with the Walsh symbol W to provide decovered half-symbols. The decovered half-symbols are then demodulated with a conjugated complex pilot $\hat{h}_1^*$ recovered by correlator 610a to provide demodulated half-symbols, which are then provided to a switch 620a. In the first half of the STS symbol period, switch 620a is in position A, and the demodulated half-symbol is provided to a signal path 622a and the inverted demodulated half-symbol is provided to a signal path 622b. In the second half of the STS symbol period, switch 620a is in position B, and the demodulated half-symbol is provided to signal paths 622a and 622b. Switch 620a can be implemented with a demultiplexer or some other element.

The demodulated half-symbols on signal path 622a are provided to an accumulator 642a within a combiner 640. The demodulated half-symbols on signal path 622b are provided to a complex conjugator 626a, which conjugates the received half-symbols and provides the conjugated half-symbols to an accumulator 642b within combiner 640.

Correlator 610b processes the complex received samples in similar manner as correlator 610a. Specifically, correlator 610b despreads the complex received samples with a despreading sequence PN_2, decovers the despread samples with the Walsh symbol W to provide decovered half-symbols, and demodulates the decovered half-symbols with a conjugated complex pilot $\hat{h}_2^*$ recovered by correlator 610b to provide demodulated half-symbols. The demodulated half-symbols corresponding to the first half of the STS symbol period are provided to accumulator 642b, and also conjugated and provided to accumulator 642a. Similarly, the demodulated half-symbols corresponding to the second half of the STS symbol period are provided to accumulator 642b, and also inverted and conjugated and provided to accumulator 642a.

For each STS symbol period, accumulator 642a combines the four received demodulated half-symbols and provides an even output symbol, and accumulator 642b combines the four received demodulated half-symbols to provide an odd output symbol.

Demodulator architecture 600 generates equivalent results as demodulator architecture 500 in FIG. 5. However, by performing the pilot demodulation after the decovering, only one complex multiplier is required. Complex multiplier 616 performs one complex multiply (e.g., one dot product and one cross product) for each half of the STS symbol period (i.e., each period

of T). In contrast, each of multipliers 528 in demodulator architecture 500 performs one complex multiply for each STS symbol period of 2T.

Also, the summers (i.e., summers 524) used to combine the decovered half-symbols for each STS symbol period are not needed in demodulator architecture 600 since this function is performed by accumulators 642a and 642b. Each accumulator 642 performs twice the number of read-accumulate-write operations for each STS symbol period as accumulator 542 in demodulator architecture 500.

FIG. 7 is a block diagram of yet another specific embodiment of a demodulator architecture 700 of the invention, which is also capable of demodulating a downlink data transmission that has been processed in the STS mode of the CDMA-2000 standard. The complex sample stream is provided to correlators 710a and 710b, with each correlator 710 operated to receive, track, and demodulate a signal transmitted from one of the transmit antennas.

Within each correlator 710, the complex received samples are despread by a complex multiplier 712 with a despreading sequence PN having a particular time offset assigned to that correlator, decovered by a decover element 714 with the Walsh symbol W to provide decovered half-symbols, and demodulated by a complex multiplier 716 with a conjugated complex pilot $\hat{h}^*$ recovered by that correlator to provide demodulated half-symbols.

Within correlator 710a, a switch 720a provides demodulated half-symbols corresponding to the first half of the STS symbol period to an accumulator 742a within a combiner 740 and further provides demodulated half-symbols corresponding to the second half of the STS symbol period to an accumulator 742b within combiner 740. Similarly, within correlator 710b, a switch 720b provides demodulated half-symbols corresponding to the first half of the STS symbol period to an accumulator 742c and demodulated half-symbols corresponding to the second half of the STS symbol period to an accumulator 742d. Each accumulator 742 selectively combines the received half-symbols to provide the output symbols.

In FIG. 7, complex multipliers 716a and 716b are each configured to perform two complex multiplies for each STS symbol period. The complex multiply from correlator n for time interval Tx of the STS symbol period can be expressed as:

$$
\begin{aligned}
C^{n} &= \left(X_I + jX_Q\right)\left(P_I - jP_Q\right) \quad , \\
&= \left(X_I P_I + X_Q P_Q\right) + j\left(X_Q P_I - X_I P_Q\right) \quad , \\
&= C_{dot}^{n,Tx} + j\, C_{cross}^{n,Tx} \quad ,
\end{aligned}
\qquad \text{Eq (20)}
$$

where $X_I + jX_Q$ is the complex decovered half-symbol to be demodulated, $P_I - jP_Q$ is the conjugated pilot estimate (e.g., $\hat{h}^* = P_I - jP_Q$), and $C_{dot}^{n,Tx}$ and $C_{cross}^{n,Tx}$ are the dot and cross products, respectively, for the complex multiply.

As shown in equation (20), each complex multiply can be performed with a dot product and a cross product. The four complex multiplies performed by multipliers 716a and 716b for each STS symbol period can be achieved with four dot products and four cross products, which yield four "dot" symbols and four "cross" symbols, respectively. The dot and cross symbols are also referred to as intermediate symbols. In an embodiment, the eight intermediate symbols for each STS symbol period can be stored to eight memory locations and later combined when the symbols are retrieved from memory.

The symbol combination performed by accumulators 742 can be computed as follows. In correlator 710a, the dot and cross products generate the intermediate symbols $C_{dot}^{1,T1}$ and $C_{cross}^{1,T1}$, respectively, in the first half of the STS symbol period and the intermediate symbols $C_{dot}^{1,T2}$ and $C_{cross}^{1,T2}$, respectively, in the second half of the STS symbol period. Similarly, in correlator 710b, the dot and cross products generate the intermediate symbols $C_{dot}^{2,T1}$ and $C_{cross}^{2,T1}$, respectively, in the first half of the STS symbol period and the intermediate symbols $C_{dot}^{2,T2}$ and $C_{cross}^{2,T2}$, respectively, in the second half of the STS symbol period. The even complex output symbols C_{even} can be expressed as:

$$
\begin{aligned}
C_{even} &= C_{even}^{I} + jC_{even}^{Q} \quad , \\
C_{even}^{I} &= C_{dot}^{1,T1} + C_{dot}^{1,T2} + C_{dot}^{2,T1} - C_{dot}^{2,T2} \quad , \text{ and} \\
C_{even}^{Q} &= C_{cross}^{1,T1} + C_{cross}^{1,T2} - C_{cross}^{2,T1} + C_{cross}^{2,T2} \quad .
\end{aligned}
\qquad \text{Eq (21)}
$$

Similarly, the odd complex output symbols C_{odd} can be expressed as:

$$
\begin{aligned}
C_{odd} &= C_{odd}^{I} + jC_{odd}^{Q} \quad , \\
C_{odd}^{I} &= -C_{dot}^{1,T1} + C_{dot}^{1,T2} + C_{dot}^{2,T1} + C_{dot}^{2,T2} \quad , \text{ and} \\
C_{odd}^{Q} &= C_{cross}^{1,T1} - C_{cross}^{1,T2} + C_{cross}^{2,T1} + C_{cross}^{2,T2} \quad .
\end{aligned}
\qquad \text{Eq (22)}
$$

To further simplify the computations, equations (21) and (22) may be expressed as:

$$
\begin{aligned}
C^{I}_{even} &= \left(C^{1,T1}_{dot} + C^{1,T2}_{dot} + C^{2,T1}_{dot} + C^{2,T2}_{dot}\right) - 2C^{2,T2}_{dot} \quad , \\
C^{Q}_{even} &= \left(C^{1,T1}_{cross} + C^{1,T2}_{cross} + C^{2,T1}_{cross} + C^{2,T2}_{cross}\right) - 2C^{2,T1}_{cross} \quad , \\
C^{I}_{odd} &= \left(C^{1,T1}_{dot} + C^{1,T2}_{dot} + C^{2,T1}_{dot} + C^{2,T2}_{dot}\right) - 2C^{1,T1}_{dot} \quad , \\
C^{Q}_{odd} &= \left(C^{1,T1}_{cross} + C^{1,T2}_{cross} + C^{2,T1}_{cross} + C^{2,T2}_{cross}\right) - 2C^{1,T2}_{cross} \quad .
\end{aligned}
\qquad \text{Eq (23)}
$$

In equation (23), the quantity within the parenthesis can be computed once for the dot products and once for the cross products for each STS symbol period. Two such combined symbols can be computed for each STS symbol period. For each output symbol (e.g., C^{I}_{even}), a corresponding intermediate symbol (e.g., $C^{2,T2}_{dot}$) is scaled by a factor of two (e.g., shifted left by one bit) and subtracted from a corresponding combined symbol (e.g., $C^{1,T1}_{dot} + C^{1,T2}_{dot} + C^{2,T1}_{dot} + C^{2,T2}_{dot}$).

FIGS. 5, 6, and 7 show three specific embodiments of the present invention. Other embodiments can also be designed and are within the scope of the present invention. Generally, the demodulator architectures of the present invention perform partial processing (e.g., despreading, decovering, pilot demodulation, or a combination thereof) on fractions (e.g., half, quarter, and so on) of the STS symbol period to generate processed "partial-symbols". The processed partial-symbols are then appropriately further processed and combined to generate the output symbols. By performing partial processing on each fraction of the STS symbol period, numerous benefits described above are achieved.

The present invention has been described with designs in which the partial processing is performed on half-symbols. However, partial processing on other fractions of the symbol period may also be performed and are within the scope of the present invention. For example, the partial processing may be performed on quarter symbol period, eighth symbol period, or some other fraction.

In the embodiments shown in FIGS. 5, 6, and 7, two correlators are used to process the two signals transmitted from two antennas. Each of these correlators can be operated to track the timing corresponding to the signal instances being processed.

The signals from the two transmit antennas may also be processed based on the same timing (e.g., the timing of one of the signal instances being

processed, or the average timing of the two signal instances, or others). In this implementation, the same symbols are used for both transmitted signals, and the processing can be performed by a single (modified) correlator. The modified correlator can be designed to perform despreading and decovering with a particular time offset, and two pilot demodulation. Common sampling, decimation, despreading, and decovering are performed for both transmitted signals. The use of the same timing may result in higher cancellation of cross-talk, which can provide improved performance.

The demodulator architectures of the invention can be employed in various receiver architectures such as, for example, a rake receiver. The design and operation of a rake receiver for an CDMA system is described in further detail in U.S. Patent No. 5,764,687, entitled "MOBILE DEMODULATOR ARCHITECTURE FOR A SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM," and U.S. Patent No. 5,490,165, entitled "DEMODULATION ELEMENT ASSIGNMENT IN A SYSTEM CAPABLE OF RECEIVING MULTIPLE SIGNALS," both assigned to the assignee of the present invention and incorporated herein by reference.

The rake receiver typically includes many correlators (i.e., fingers) that are assigned to process strong instances of the received signal. The demodulator architectures of the invention allow for easy combining of symbols or half-symbols from multiple assigned correlators. For example, referring back to FIG. 4, the even complex symbols from each assigned correlator are provided to accumulator 442a and the odd complex symbols from each assigned correlator are provided to accumulator 442b. For each STS symbol period, each accumulator 442 combines all received symbols and provides a complex output symbol. Generally, the rake receiver using the demodulator architectures of the invention can be designed to include as many correlators as desired. Each accumulator is then designed to accumulate symbols from all assigned correlators.

The processing to recover the transmitted pilot is known in the art and not described in detail herein. The pilot processing is dependent in the particular CDMA system or standard being implemented. For example, different pilot processing is typically performed depending on whether the pilot is added to (i.e., superimposed over) the data or time division multiplexed with the data. An example of the pilot processing is described in the aforementioned U.S. Patent Application Serial No. 5,764,687 and 5,490,165.

For clarity, the demodulator architectures, demodulators, and receiver units of the invention have been described specifically for the STS mode defined

by the CDMA-2000 standard. The invention can also be used in other communications systems that employ the same, similar, or different transmit diversity modes. The demodulator architecture of the invention can be used to provide the basic functionality (e.g., decovering, pilot demodulation, and so on). Modification of the basic functionality and/or additional processing (e.g., combining, reordering of the symbols, and so on) may be implemented to achieve the desired results.

For example, the W-CDMA standard provides a space time block coding transmit antenna diversity (STTD) mode in which symbols are transmitted redundantly over two antennas. In the STTD mode, data symbols are redundantly sent to two modulators, but the symbols provided to the second modulator are reordered, with respect to the symbols provided to the first modulator, in accordance with a particular ordering scheme. To support the STTD mode, demodulator architectures of the invention can be modified to temporarily store the demodulated symbols from the assigned correlators, reorder the symbols in the inverse manner, and combine the symbols to recover the transmitted symbols.

The demodulator architectures described above can be advantageously used in a user terminal (e.g., a mobile unit, a telephone, and so on) of a communications system, and may also be used at a base station. The signal processing for the downlink and uplink may be different and is typically dependent on the particular CDMA standard or system being implemented. Thus, the demodulator architectures are typically adopted especially for the particular application for which it is used.

Some or all of the elements described above for the demodulator architectures of the invention (e.g., the complex multipliers, decover elements, switches, delay elements, summers, combiner, and so on) can be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), controllers, micro-controllers, microprocessors, programmable logic devices (PLDs), other electronic units designed to perform the functions described herein, or a combination thereof. Also, some or all of the elements described above can be implemented using software or firmware executed on a processor.

As an example, a demodulator can be designed in which the despreader and decoverer elements for each correlator are implemented in hardware, and the pilot demodulation and symbol accumulation for all correlators are performed by a DSP in a time division multiplexed manner. As another example, one correlator and combiner can be implemented and used to process

samples corresponding to various signal instances in a time division multiplexed manner. Numerous other implementations can be contemplated and are within the scope of the present invention.

The foregoing description of the preferred embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without the use of the inventive faculty. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

CLAIMS

1. A demodulator for processing a received signal in a wireless communications system, comprising:

a plurality of correlators, each correlator operative to receive and decover a plurality of input samples generated from the received signal to provide decovered half-symbols, and to demodulate the decovered half-symbols with pilot estimates to generate correlated symbols, wherein the decovering is performed with a channelization symbol having a length (T) that is half the length (2T) of a channelization symbol used to cover data symbols in the received signal; and

a combiner coupled to the plurality of correlators, the combiner operative to receive correlated symbols from each of the plurality of correlators and to selectively combine the correlated symbols to provide demodulated symbols.

2. The demodulator of claim 1, wherein each correlator is further operative to receive and despread the plurality of input samples with a respective despreading sequence to provide a plurality of despread samples, and

wherein the decovering is performed by the correlators on the plurality of despread samples.

3. The demodulator of claim 2, wherein the despreading and decovering are performed based on a common timing.

4. The demodulator of claim 1, wherein one of the correlators is operative to receive and decover the plurality of input samples generated from the received signal to provide the decovered half-symbols, and wherein each correlator is operative to receive and demodulate the decovered half-symbols with a pilot estimate from the correlator to generate correlated symbols

5. The demodulator of claim 1, wherein the received signal includes data symbols that have been covered with a Walsh symbol W_{STS} having a length of 2T and data symbols that have been covered with a complementary Walsh symbol $\overline{W}_{STS}$ also having a length of 2T.

6. The demodulator of claim 1, wherein the received signal includes a first signal transmitted from a first antenna and a second signal transmitted from a second antenna, and wherein the demodulator comprises one or more correlators assigned to process one or more instances of the first signal and one or more correlators assigned to process one or more instances of the second signal.

7. The demodulator of claim 1, wherein the pilot estimates used within each correlator to demodulate the decovered half-symbols are generated based on a signal instance being processed by that correlator.

8. The demodulator of claim 1, wherein the received signal conforms to CDMA-2000 standard or W-CDMA standard.

9. A demodulator for processing a received signal in a communications system, the demodulator comprising:

a plurality of correlators, each correlator operative to receive and demodulate a plurality of input samples generated from the received signal to provide first and second symbol streams, wherein each correlator includes

a decover element operative to receive and decover the plurality of input samples to provide pairs of decovered half-symbols, wherein the decovering is performed with a Walsh symbol W having a length (T) that is half the length (2T) of a Walsh symbol W_{STS} used to cover data symbols in the received signal, and wherein one pair of decovered half-symbols is provided for each Walsh symbol period of 2T,

first and second summers operatively coupled to the decover element, each summer operative to combine each pair of decovered half-symbols in a particular manner to provide a respective decovered symbol, and

first and second multipliers respectively coupled to the first and second summers, each multiplier operative to receive and demodulate decovered symbols from the respective summer with a respective pilot to provide the first or second symbol stream; and

a combiner coupled to the plurality of correlators, the combiner operative to receive the first and second symbol streams from the first and second multipliers, respectively, of each of the plurality of correlators, combine the first symbol streams from the plurality of correlators to provide a first

output symbol stream, and combine the second symbol streams from the plurality of correlators to provide a second output symbol stream.

10. The demodulator of claim 9, wherein each correlator further includes

a despreader operative to receive and despread the plurality of input samples with a particular despreading sequence to provide a plurality of despread samples, and

wherein the decover element is coupled to the despreader and operative to receive and decover the plurality of despread samples.

11. The demodulator of claim 9, wherein each correlator further includes

a switch coupled to the decover element and operative to

receive the pairs of decovered half-symbols,

provide decovered half-symbols corresponding to a first half of the Walsh symbol period of 2T to a first output, and

provide decovered half-symbols corresponding to a second half of the Walsh symbol period of 2T to a second output, and

wherein the first and second summers are operatively coupled to the first and second outputs, respectively, of the switch.

12. The demodulator of claim 11, wherein each correlator further includes

a delay element coupled to the first output of the switch and the first summer.

13. A demodulator for processing a received signal in a communications system, the demodulator comprising:

a plurality of correlators, each correlator operative to receive and demodulate a plurality of input samples generated from the received signal to provide first and second symbol streams, wherein each correlator includes

a decover element operative to receive and decover the plurality of input samples to provide pairs of decovered half-symbols, wherein the decovering is performed with a Walsh symbol W having a length (T) that is half the length (2T) of a Walsh symbol W_{STS} used to cover data symbols in the received signal, and wherein one pair of decovered half-symbols is provided for each Walsh symbol period of 2T,

a multiplier coupled the decover element and operative to receive and demodulate the decovered half-symbols with a pilot recovered by the correlator to provide demodulated half-symbols, and

a switch coupled to the multiplier and operative to provide a first combination of decovered half-symbols for each Walsh symbol period of 2T in a first symbol stream and to provide a second combination of decovered half-symbols for each Walsh symbol period of 2T in a second symbol stream; and

a combiner coupled to the plurality of correlators, the combiner operative to receive the first and second symbol streams from each of the plurality of correlators, combine the first symbol streams from the plurality of correlators to provide a first output symbol stream, and combine the second symbol streams from the plurality of correlators to provide a second output symbol stream.

14. The demodulator of claim 13, wherein each correlator further includes

a despreader operative to receive and despread the plurality of input samples with a particular despreading sequence to provide a plurality of despread samples, and

wherein the decover element is coupled to the despreader and operative to receive and decover the plurality of despread samples.

15. The demodulator of claim 13, wherein the multiplier in each correlator is operative to perform a dot product between the decovered half-symbols and the pilot to provide dot symbols, and to perform a cross product between the decovered half-symbols and the pilot to provide cross symbols, and

wherein the combiner is operative to selectively combine dot symbols and cross symbols for each Walsh symbol period of 2T to provide demodulated symbols for the first and second output symbol streams.

16. A correlator for processing a received signal in a communications system, comprising:

a decover element operative to receive and decover a plurality of input samples generated from the received signal to provide pairs of decovered half-symbols, wherein the decovering is performed with a channelization symbol having a length (T) that is half the length (2T) of a channelization symbol used

to cover data symbols in the received signal, and wherein one pair of decovered half-symbols is provided for each channelization symbol period of 2T; and

one or more multipliers operatively coupled to the decover element, each multiplier operative to receive and demodulate decovered half-symbols with a respective pilot to provide correlated symbols.

17. The correlator of claim 16, further comprising:

a despreader operative to receive and despread the plurality of input samples with a despreading sequence to provide a plurality of despread samples, and

wherein the decover element is coupled to the despreader and operative to receive and decover the plurality of despread samples.

18. A correlator for processing a received signal in a communications system, comprising:

a despreader operative to receive and despread the plurality of input samples with a despreading sequence to provide a plurality of despread samples;

a decover element coupled to the despreader and operative to receive and decover a plurality of despread samples to provide pairs of decovered half-symbols, wherein the decovering is performed with a Walsh symbol W having a length (T) that is half the length (2T) of the Walsh symbols W_{STS} and $\overline{W}_{STS}$ used to cover data symbols in the received signal, and wherein one pair of decovered half-symbols is provided for each Walsh symbol period of 2T; and

a multiplier operatively coupled to the decover element and operative to receive and demodulate decovered half-symbols with a pilot to provide correlated symbols.

19. A receiver unit in a wireless communications system, comprising:

a receiver operative to process a received signal to provide a plurality of samples; and

a demodulator coupled to the receiver and operative to receive and demodulate the plurality of samples to provide demodulated symbols, the demodulator including

a plurality of correlators, each correlator operative to receive and decover the plurality of samples to provided decovered symbols or half-symbols and to demodulate the decovered symbols or half-symbols with a respective pilot to generate correlated symbols, wherein the decovering

is performed with a Walsh symbol W having a length (T) that is half the length (2T) of a Walsh symbol W_{STS} used to cover data symbols in the received signal, and

a combiner coupled to the plurality of correlators and operative to receive correlated symbols from each of the plurality of correlators and to selectively combine the correlated symbols to provide the demodulated symbols.

20. The receiver unit of claim 19, wherein each correlator is further operative to despread the plurality of samples with a particular despreading sequence to generate despread samples, and wherein the decovering is performed on the plurality of despread samples.

21. The receiver unit of claim 19,

wherein each correlator is further operative to provide a first combination of decovered half-symbols for each Walsh symbol period of 2T in a first symbol stream and to provide a second combination of decovered half-symbols for each Walsh symbol period of 2T in a second symbol stream, and

wherein the combiner is operative to combine the first symbol streams from the plurality of correlators to provide a first output symbol stream, and to combine the second symbol streams from the plurality of correlators to provide a second output symbol stream.

22. A method for processing a received signal in a wireless communications system, the method comprising:

generating a plurality of input samples from the received signal;

decovering the plurality of input samples for a particular received signal instance to generate decovered half-symbols, wherein the decovering is performed with a channelization symbol having a length (T) that is half the length (2T) of a channelization symbol used to cover data symbols in the received signal;

demodulating the decovered half-symbols with pilot estimates to generate correlated symbols; and

selectively combining correlated symbols associated with one or more signal instances to provide demodulated symbols.

23. The method of claim 22, further comprising:

despreading the plurality of input samples with a despreading sequence associated with a signal instance being processed to generate a plurality of despread samples for the signal instance, and

wherein the decovering is performed on the plurality of despread samples to generate the decovered half-symbols.

24. The method of claim 22, wherein the demodulating includes

performing a dot product between the decovered half-symbols and the pilot estimates to provide dot symbols, and

performing a cross product between the decovered half-symbols and the pilot estimates to provide cross symbols, and

wherein the dot symbols and cross symbols for each channelization symbol period of 2T are selectively combined to provide the demodulated symbols.

25. A method for processing a received signal in a wireless communications system, wherein the received signal includes a first signal transmitted from a first antenna and a second signal transmitted from a second antenna, the method comprising:

generating a plurality of input samples from the received signal;

processing at least one signal instance of each of the first and second signals to provide correlated symbols for each processed signal instance, wherein the processing for each signal instance includes

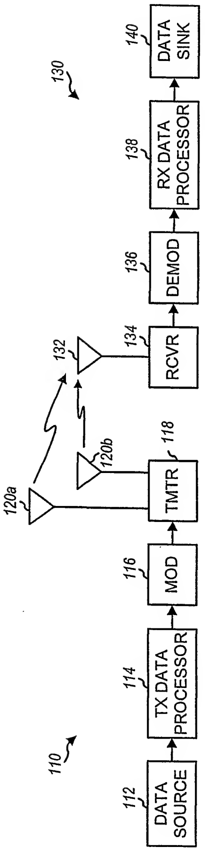
despreading the plurality of input samples with a particular despreading sequence associated with the signal instance to provide a plurality of despread samples,

decovering the plurality of despread samples to generate decovered half-symbols, wherein the decovering is performed with a Walsh symbol W having a length (T) that is half the length (2T) of a Walsh symbol W_{STS} used to cover data symbols in the received signal, and

demodulating the decovered half-symbols with pilot estimates to generate the correlated symbols for the signal instance, wherein the pilot estimates are derived from the signal instance being processed; and

selectively combining correlated symbols for the signal instances being processed to provide demodulated symbols.

100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112
DATA SOURCE
114
TX DATA PROCESSOR
116
MOD
118
TMTR
120a
120b
130
132
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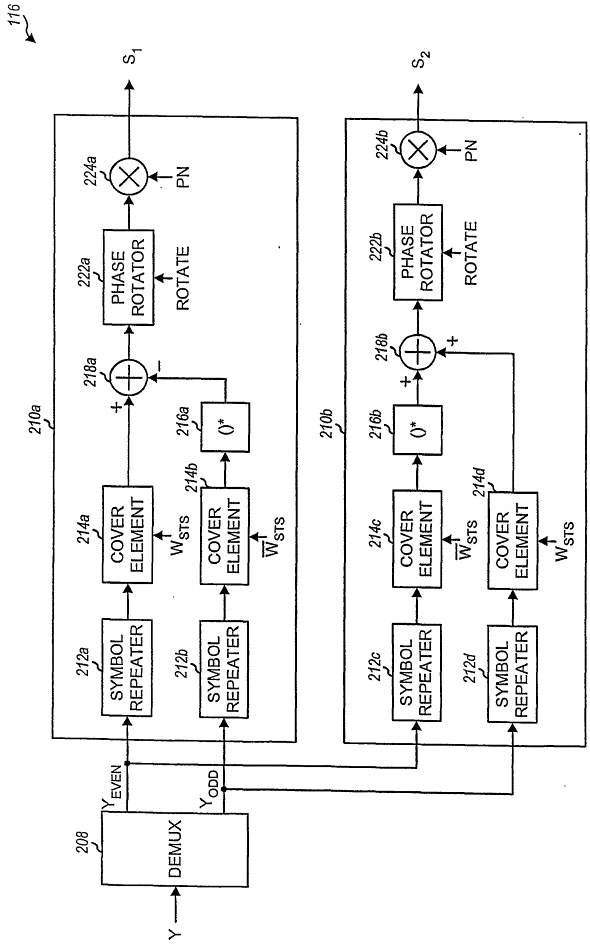
RCVR
136
DEMOD
138
RX DATA PROCESSOR
140
DATA SINK

FIG. 1


116
Y
208
DEMUX
Y_{EVEN}
Y_{ODD}
210a
212a
SYMBOL REPEATER
212b
SYMBOL REPEATER
214a
COVER ELEMENT
W_{STS}
214b
COVER ELEMENT
$\overline{W}_{STS}$
216a
()*
218a
+
-
222a
PHASE ROTATOR
ROTATE
224a
PN
S_1
210b
212c
SYMBOL REPEATER
212d
SYMBOL REPEATER
214c
COVER ELEMENT
$\overline{W}_{STS}$
214d
COVER ELEMENT
W_{STS}
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()*
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+
+
222b
PHASE ROTATOR
ROTATE
224b
PN
S_2

FIG. 2

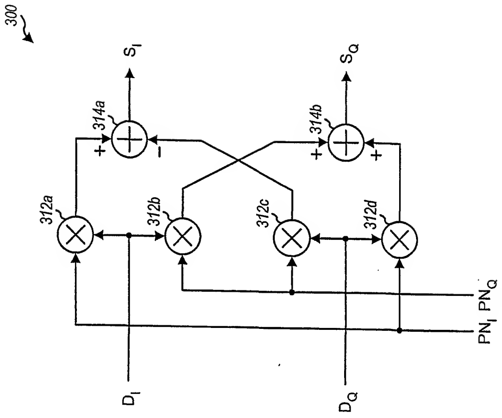
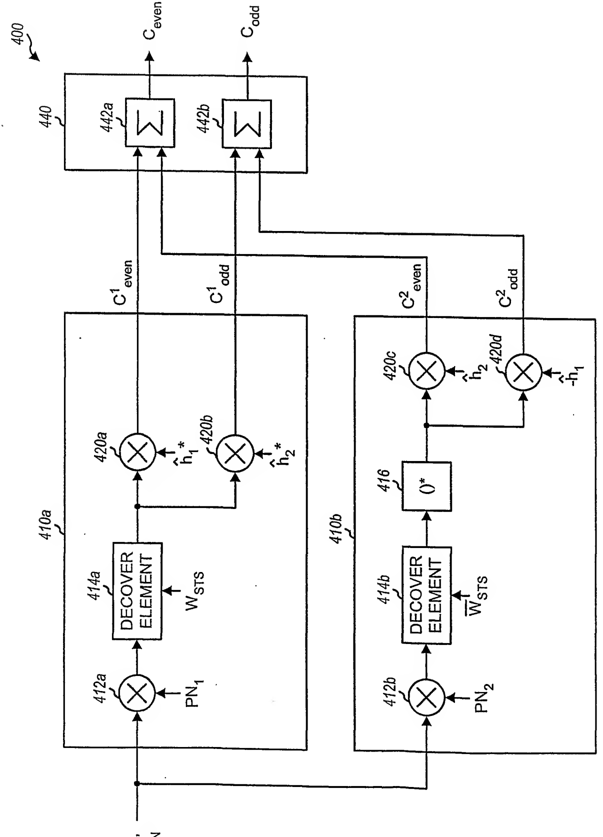


FIG. 3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442b
C_{even}
C_{odd}
410a
410b
I_{IN}, Q_{IN}
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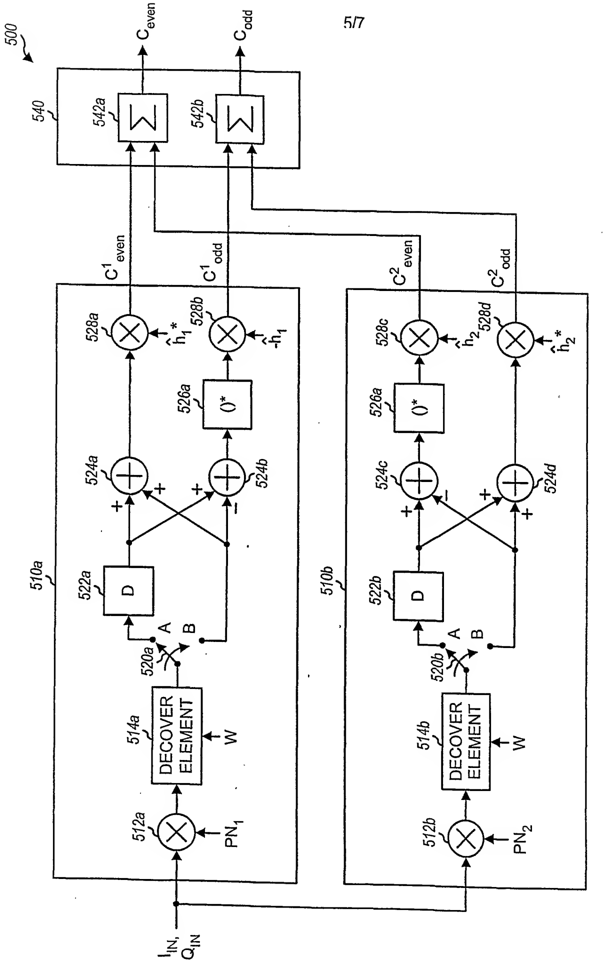
412b
PN_1
PN_2
414a
414b
DECOVER ELEMENT
DECOVER ELEMENT
W_{STS}
$\overline{W}_{STS}$
416
$()^*$
420a
420b
420c
420d
$\hat{h}_1^*$
$\hat{h}_2^*$
$\hat{h}_2$
$-\hat{h}_1$
C^1_{even}
C^1_{odd}
C^2_{even}
C^2_{odd}

FIG. 4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542a
542b
C_{even}
C_{odd}
C^1_{even}
C^1_{odd}
C^2_{even}
C^2_{odd}
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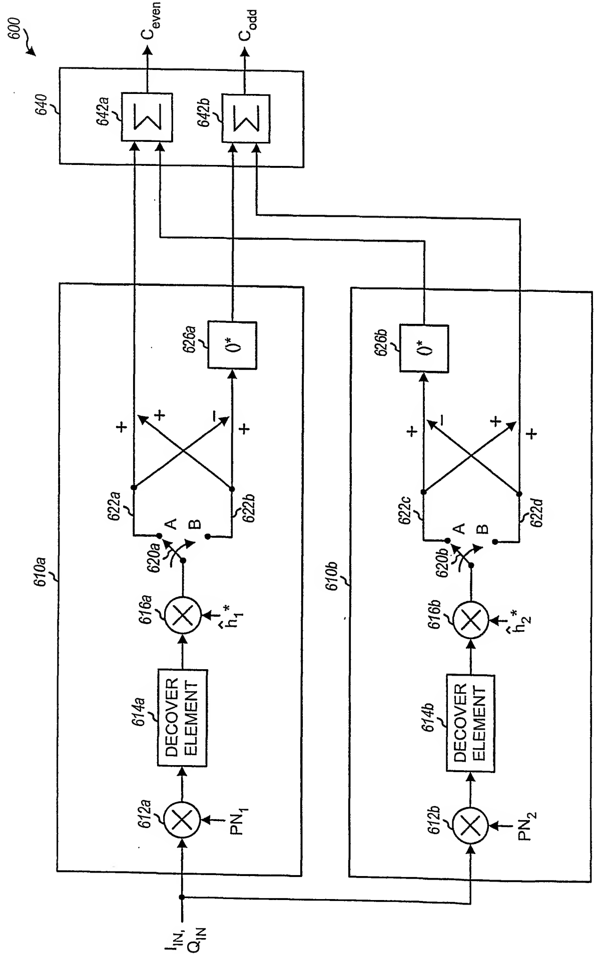
510b
512a
512b
PN_1
PN_2
514a
514b
DECOVER ELEMENT
DECOVER ELEMENT
W
W
520a
520b
A
B
A
B
522a
522b
D
D
524a
524b
524c
524d
526a
526a
$()^*$
$()^*$
528a
528b
528c
528d
$\hat{h}_1^*$
$-\hat{h}_1$
$\hat{h}_2$
$\hat{h}_2^*$
I_{IN}, Q_{IN}

FIG. 5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640
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642b
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C_{odd}
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610b
612a
612b
PN_1
PN_2
614a
614b
DECOVER ELEMENT
DECOVER ELEMENT
616a
616b
$\hat{h}_1^*$
$\hat{h}_2^*$
620a
620b
A
B
622a
622b
622c
622d
626a
626b
$()^*$
I_{IN}, Q_{IN}

FIG. 6

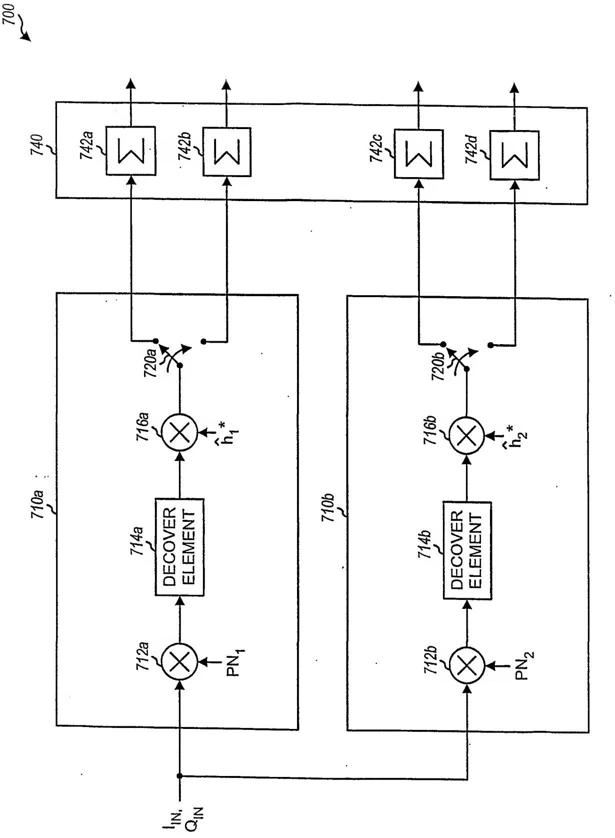
700
740
742a
742b
742c
742d
710a
710b
720a
720b
716a
716b
$\hat{h}_1^*$
$\hat{h}_2^*$
714a
714b
DECOVER ELEMENT
DECOVER ELEMENT
712a
712b
PN_1
PN_2
I_{IN}, Q_{IN}

FIG. 7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/19403

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04B1/707 H04B7/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 710 768 A (LEVIN JEFFREY A ET AL) 20 January 1998 (1998-01-20) abstract; claim 1; figures 5,12,13,15 column 13, line 25 -column 16, line 21 column 21, line 28 - line 54 column 27, line 6 - line 21 ---	1-25
A	HAYASHI M ET AL: "CDMA/TDD cellular systems utilizing a base-station-based diversity scheme" VEHICULAR TECHNOLOGY CONFERENCE, 1995 IEEE 45TH CHICAGO, IL, USA 25-28 JULY 1995, NEW YORK, NY, USA,IEEE, US, 25 July 1995 (1995-07-25), pages 799-803, XP010167052 ISBN: 0-7803-2742-X page 800, paragraph 2.2 - paragraph 2.3 -----	1,22,25

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 January 2002	16/01/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Amadei, D

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 01/19403

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